The sunny side of direct detection

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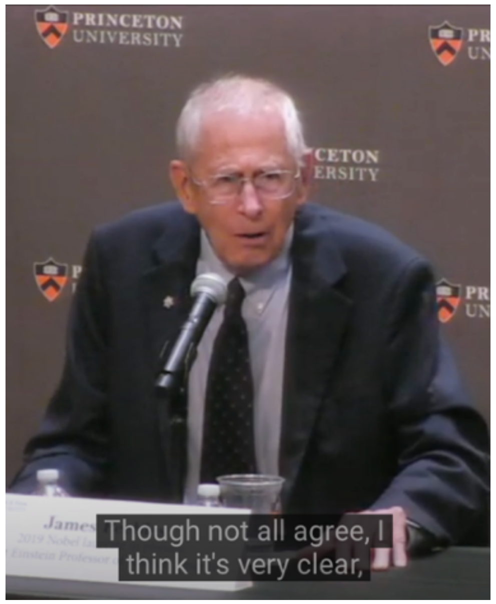
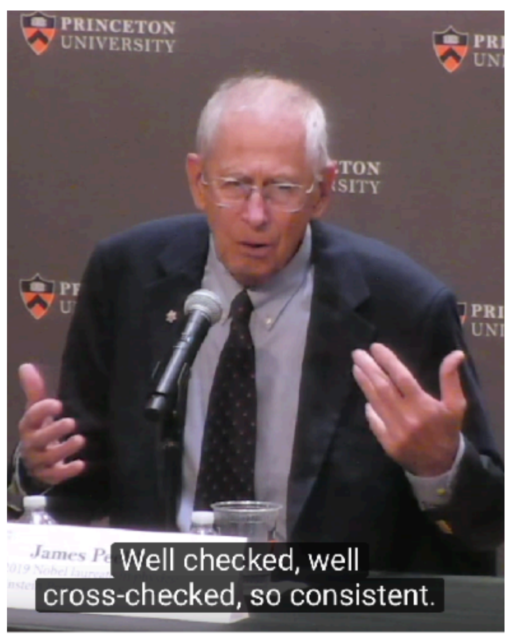
The sunny side of direct detection

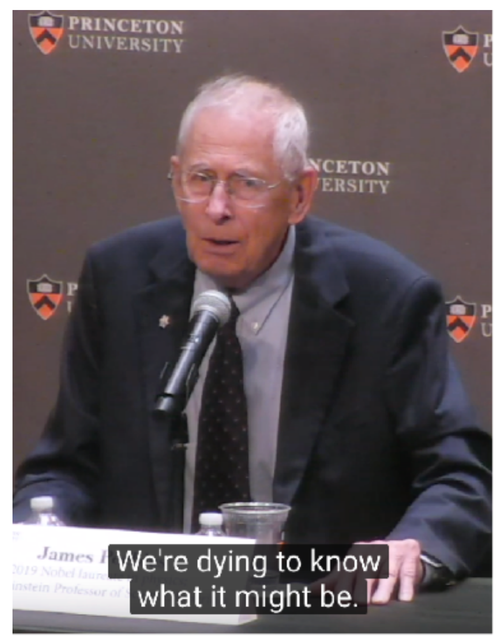
- Introduction: dark matter as the key agent in cosmological structure formation
- Introduction of dark matter direct detection
- New, irreducible signal components in direct detection

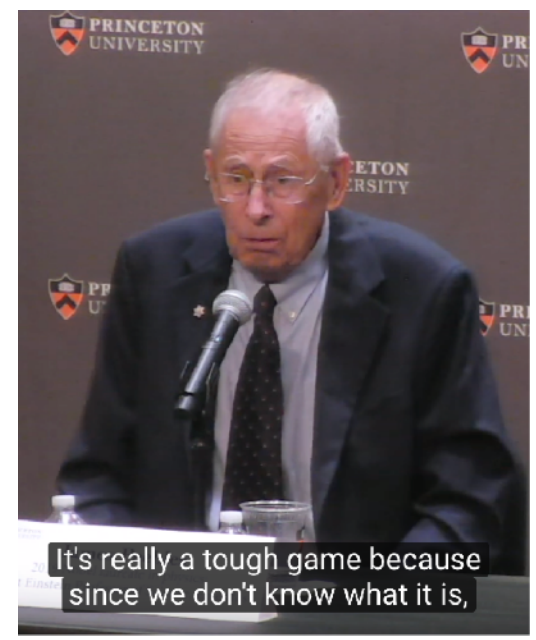
Bremsstrahlung:	Kouvaris, JP PRL 2016;
Migdal effect:	Essig, JP, Sholapurkar, Yu PRL 2020
Solar reflection I:	An, Pospelov, JP, Ritz PRL 2018
Solar reflection II:	An, Nie, Pospelov, JP, Ritz PRD 2021

Dark matter: now and then









Jim Peebles, Oct 8 2019

2019 Nobel Prize “for theoretical discoveries in physical cosmology”

Early Cosmology

Predicting the cosmic microwave background

Search for origin of chemical elements => idea in the 1940's that matter passed through a hot and dense phase and all elements were made

Alpher, Bethe, Gamow 1948

Number of reactions = cross section (cm^2) x flux of projectiles ($1/cm^2/s$) x time (s)

key reaction $p + n \to d + \gamma$

per neutron ~ not too small number to make elements

~ not too large number so that significant amounts of D and light elements are left

=> $\langle \sigma v \rangle n t \sim 1$ at $T \sim \mathrm{MeV} \sim 10^9\,\mathrm{K}$ **=> Universe filled with radiation**

with $\langle \sigma v \rangle \sim const.$ yields a prediction of the required baryon density n ~ $10^{18}/cm^3$

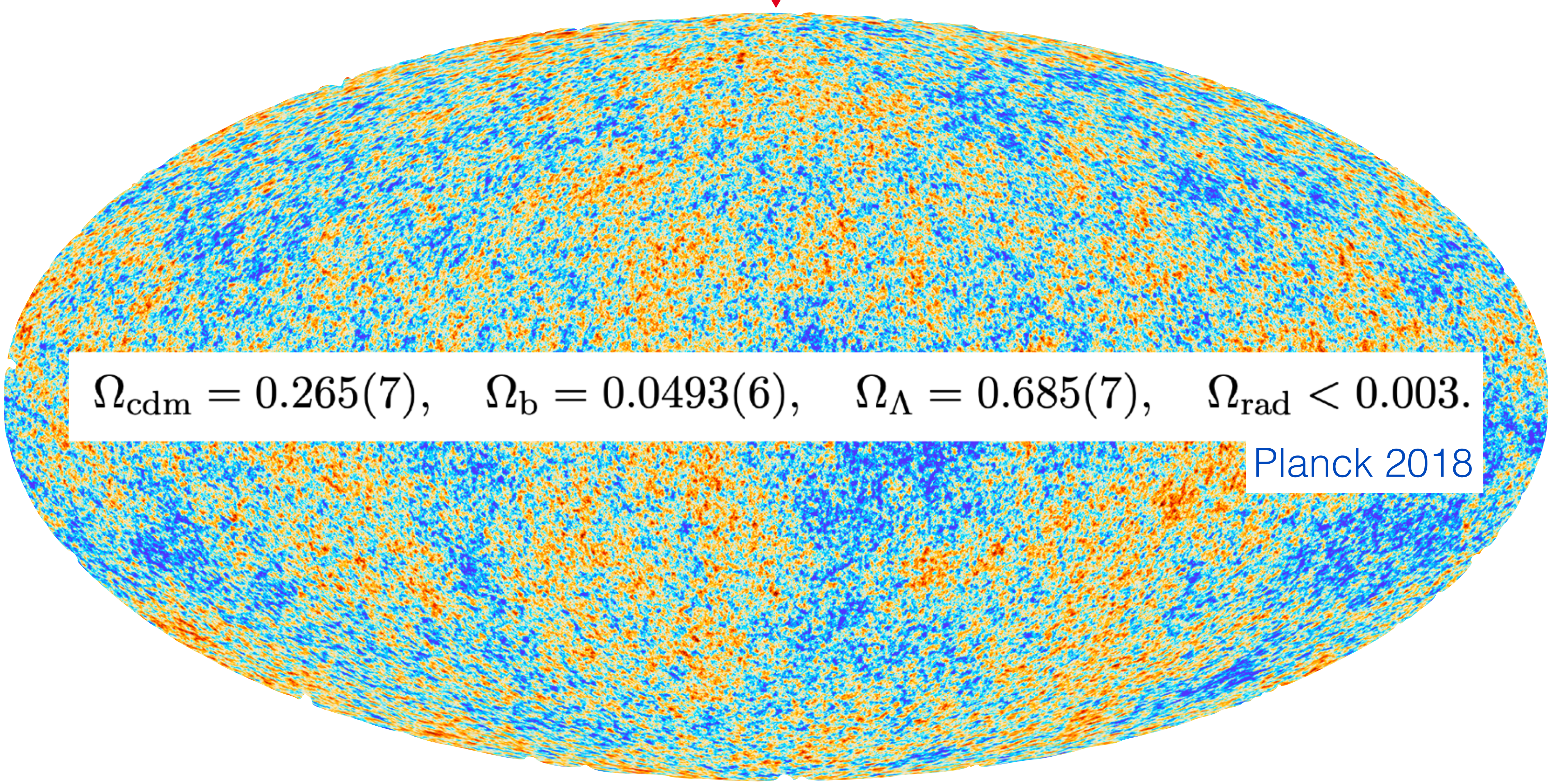
=> With an estimate of today's density n ~ $10^{-7}/cm^3$ together with $T \propto 1/a(t) \propto n^{1/3}$

=> T~ 4K today's radiation temp.

Cosmological scales

Cosmic Microwave Background

Dark Matter is the key ingredient to explain the CMB observations (linear theory)



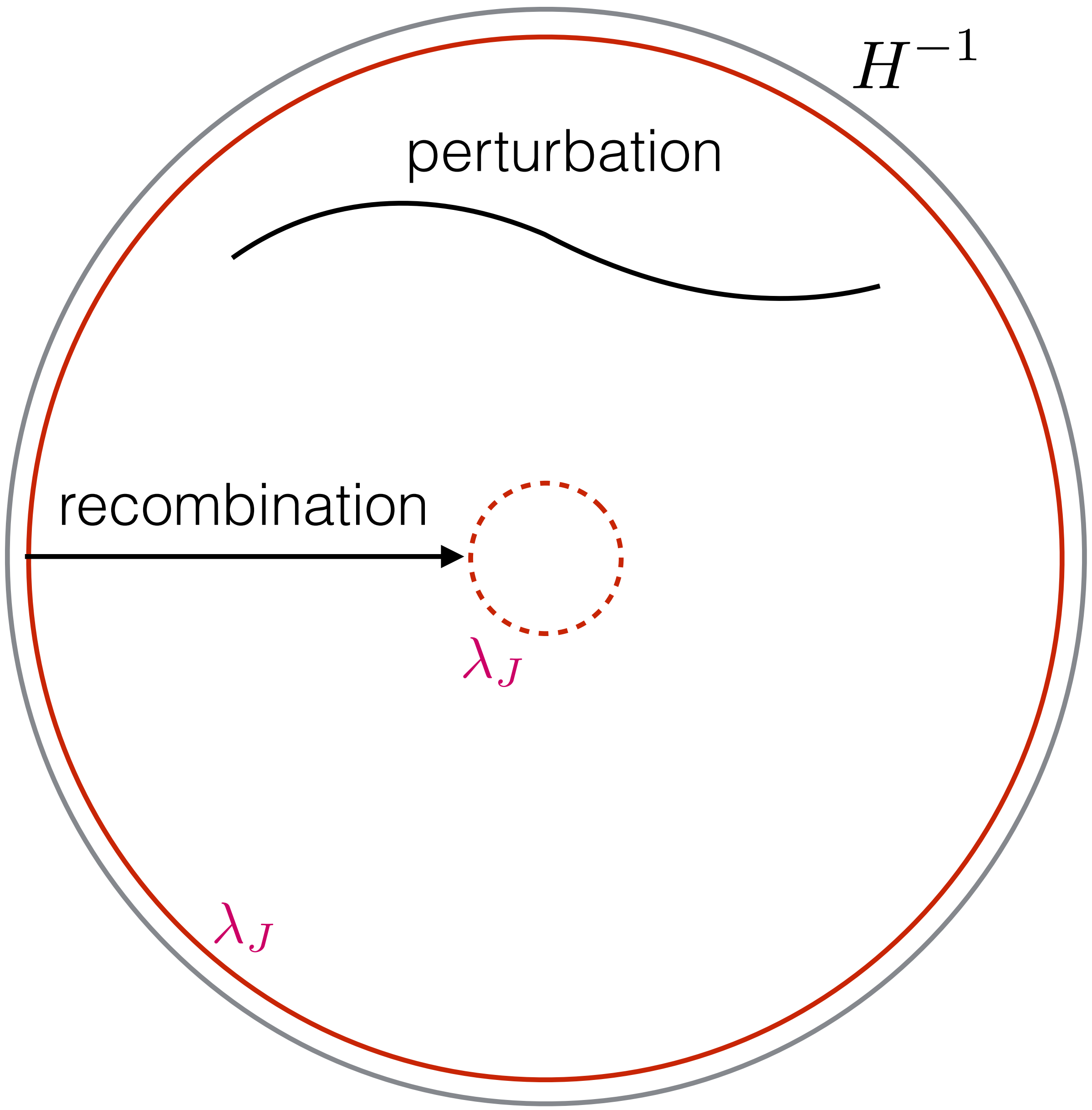
$$\Omega_{\rm cdm} = 0.265(7), \quad \Omega_{\rm b} = 0.0493(6), \quad \Omega_\Lambda = 0.685(7), \quad \Omega_{\rm rad} < 0.003.$$

Planck 2018

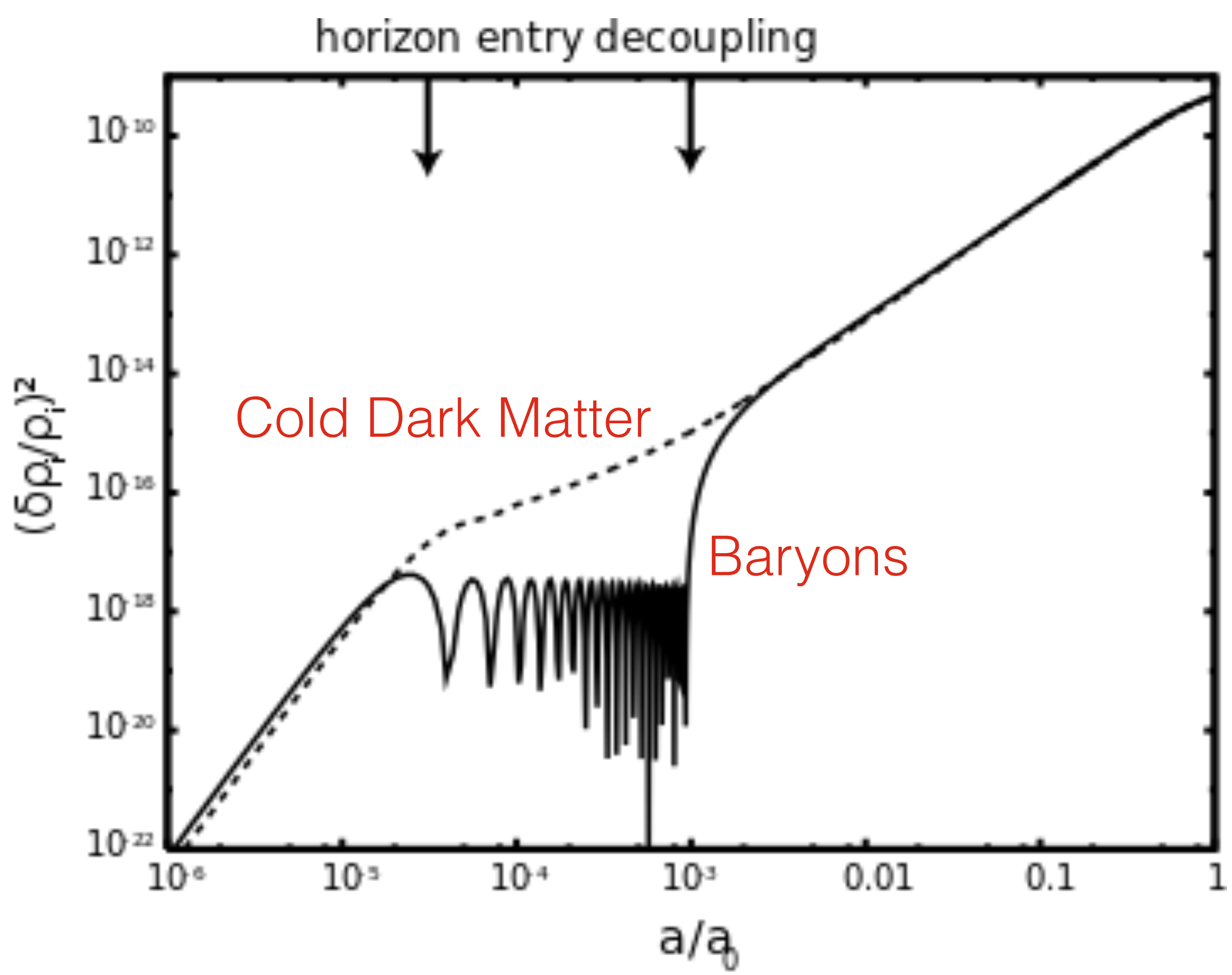
Cosmological scales

Origin of structure

$$\ddot{\delta} + [\text{Pressure} - \text{Gravity}]\,\delta = 0$$



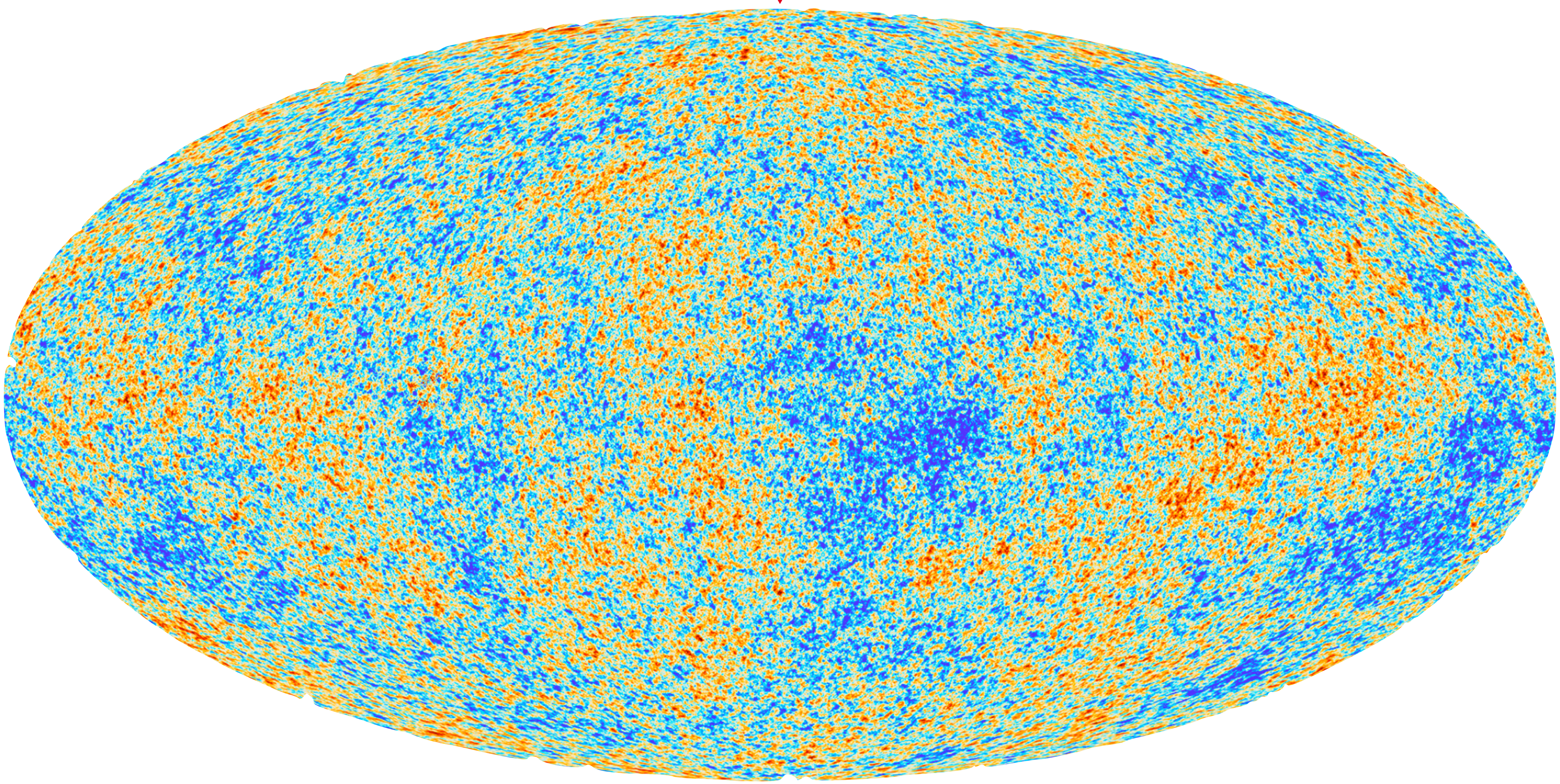
baryons fall into the potential wells created by dark matter.



Cosmological scales

Cosmic Microwave Background

Dark Matter is the key ingredient to explain the CMB observations (linear theory)

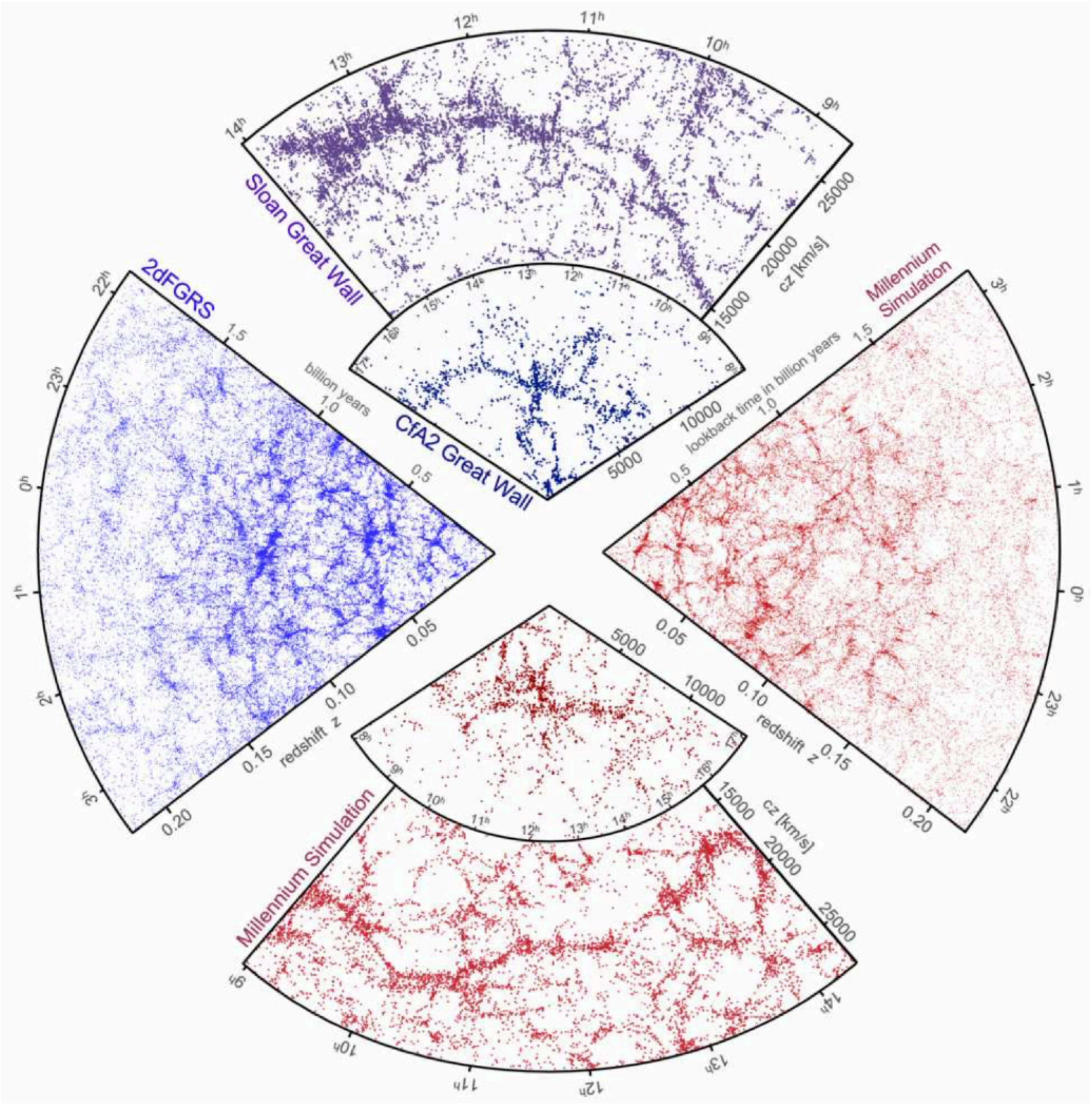


Dark Matter is the key catalyzer for formation of non-linear large scale structure

Large Scale Structure

From the CMB epoch to today

Dark Matter is the key catalyzer for formation of non-linear large scale structure



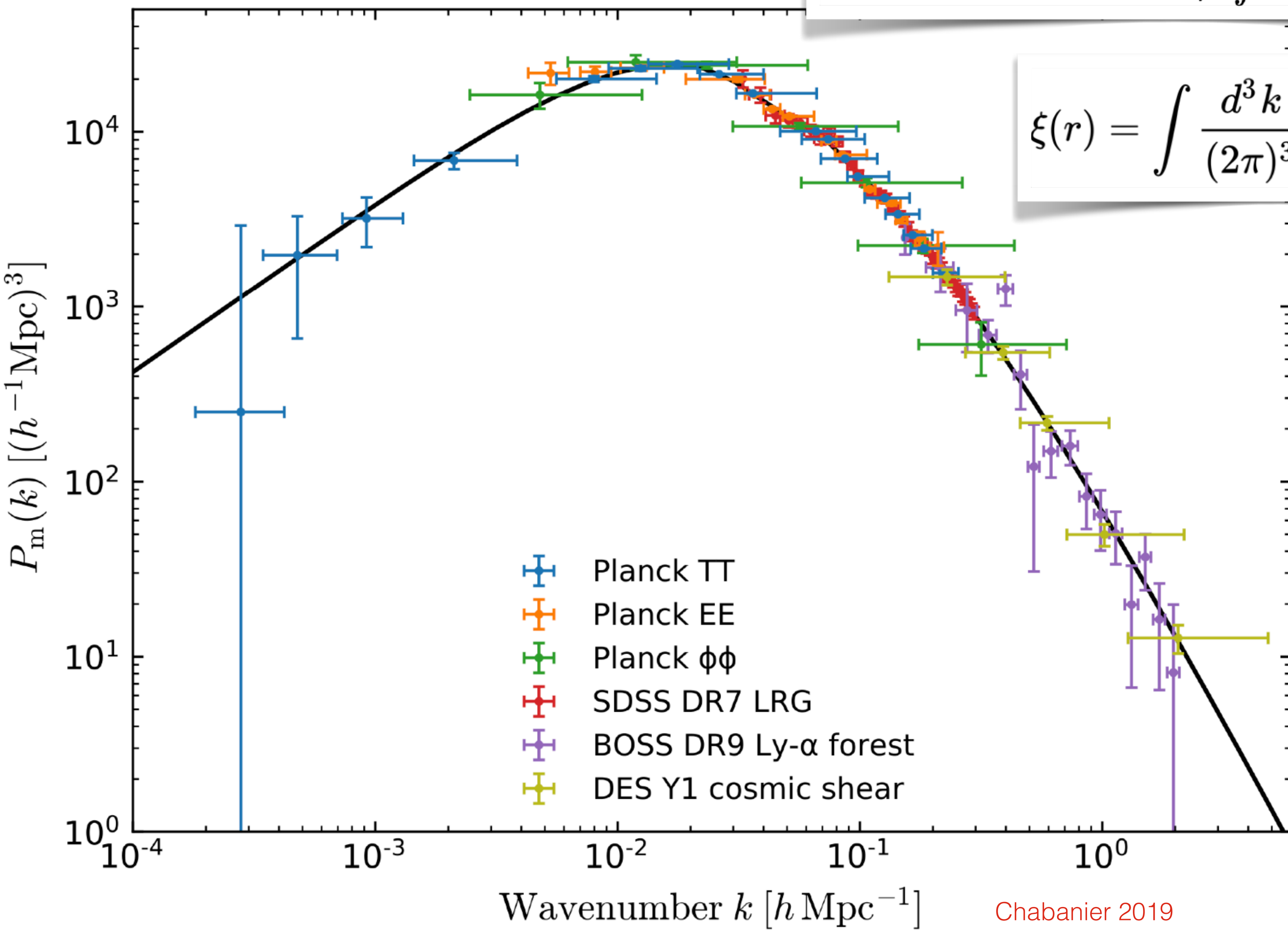
Large Scale Structure

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

Matter power spectrum

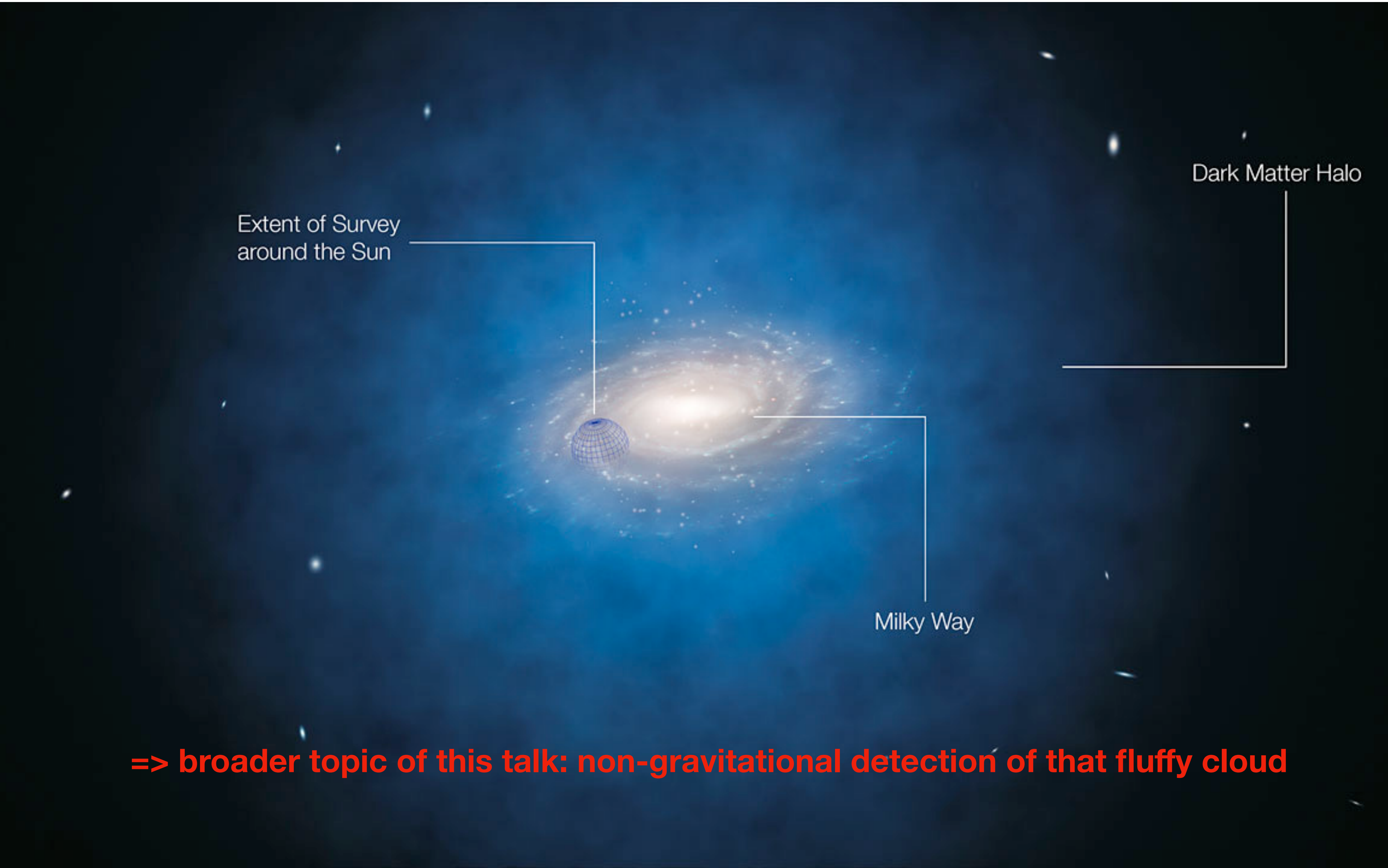
$$\xi(r) = \langle \delta(\mathbf{x})\delta(\mathbf{x}') \rangle = \frac{1}{V}\int d^3\mathbf{x}\, \delta(\mathbf{x})\delta(\mathbf{x}-\mathbf{r})$$

$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')}$$



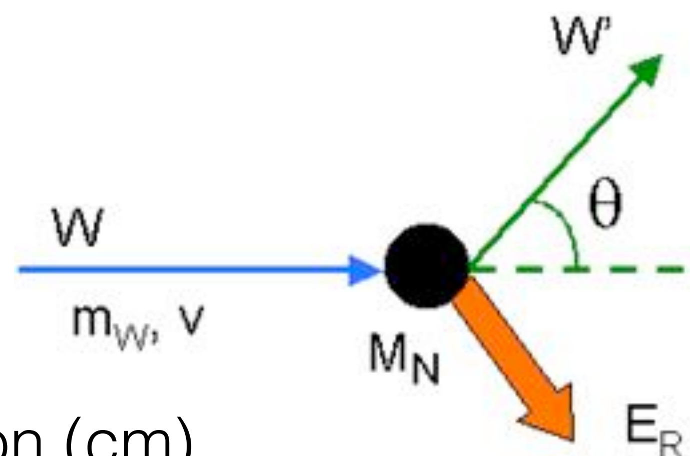
Chabanier 2019

Dark Matter in the Milky Way



=> broader topic of this talk: non-gravitational detection of that fluffy cloud

DM Direct Detection



~ keV

Basic idea

Detection Rate = particle flux (1/cm^2/sec) x cross section (cm)

$$\frac{dR(t)}{dE_R} = N_T \frac{\rho_0}{m_{\rm DM}} \int_{v \geqslant v_{\rm min}} d^3\mathbf{v}\, v\, f_{\rm LAB}(\mathbf{v}) \frac{d\sigma}{dE_R}$$

[cpd/kg/keV]

Astrophysics

local DM density

DM velocity distribution in the LAB frame

recoil cross section

Particle Physics

Contributions to f(v)

- virialized component
- substructure $(p < 10^{-4})$
- debris flow, streams

Very little is known

- largely dissipationless
- stable on cosmological timescales

DM Direct Detection

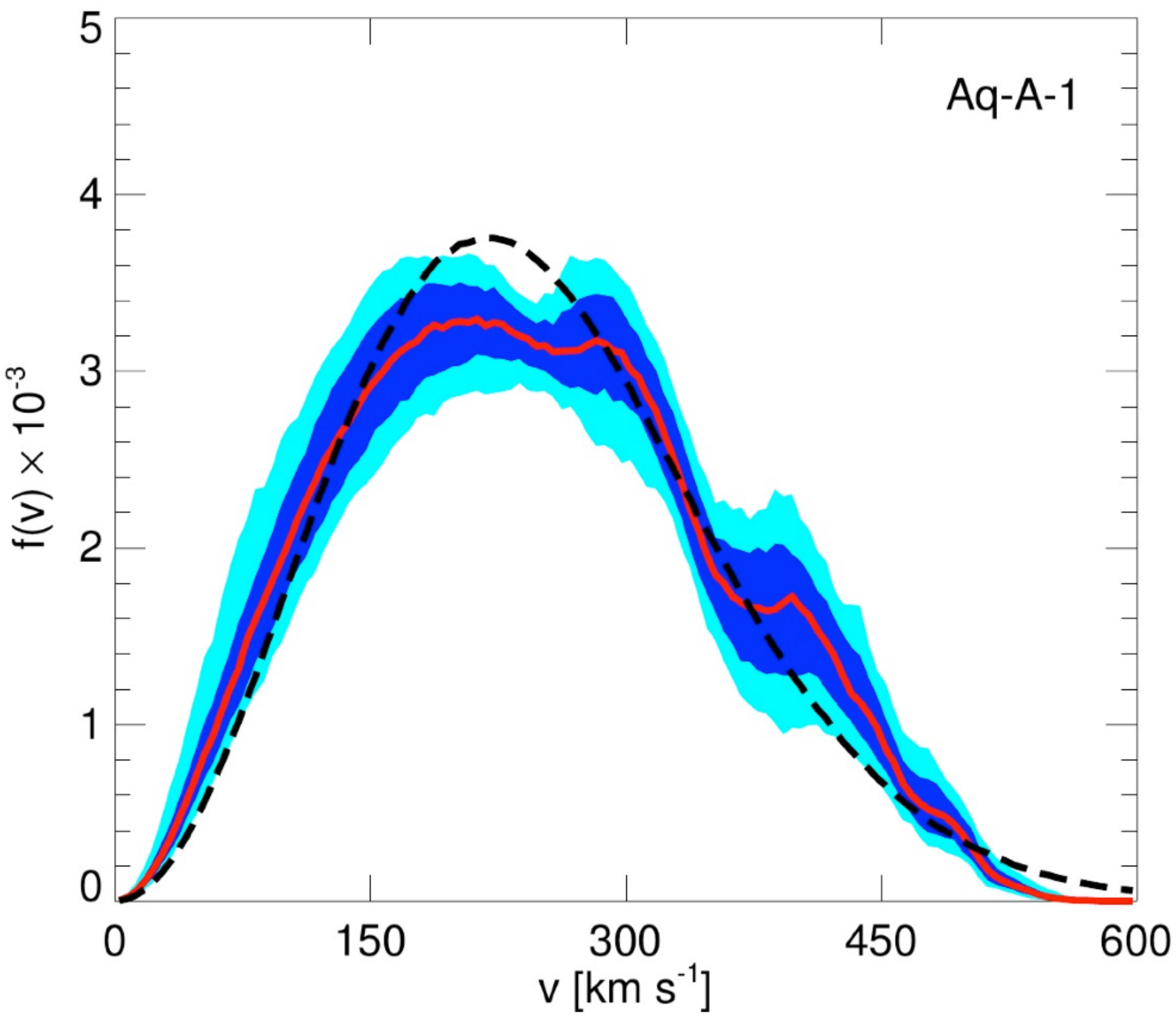
Velocity distribution of DM in the halo

Maxwellian velocity distribution is found in N-body simulations

Note: not all particles of arbitrary velocity can be gravitationally bound to the halo

$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-|\vec{v}|^2/v_0^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$$v_{\rm esc} \simeq 650\,{\rm km/s}$$



Vogelsberger et al 2009

- Local DM flux is $(v_\chi \sim 10^{-3} c)$

$$\phi_\chi \sim \frac{\rho_0 v_\chi}{m_\chi} \sim 10^5\,/{\rm cm}^2/{\rm s}\left(\frac{100\,{\rm GeV}}{m_\chi}\right)$$

Simple options for dark sectors

Connecting new physics to the Standard Model

$(H^\dagger H)\,(A\phi + \lambda\phi^2)$

"Higgs Portal"
(a minimal model of DM)

$L H N$

"Neutrino Portal"
likely realized in nature (neutrinos have mass); sterile neutrinos

$F^Y_{\mu\nu} V^{\mu\nu}$

"Vector Portal"
kinetic mixing of abelian field strength tensors

The kinetic mixing portal

"Dark Photons"

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$$

Standard Model

x "dark sector" with vector particle V^μ

$$-\frac{\kappa'}{2} F^Y_{\mu\nu} V^{\mu\nu} \xrightarrow{\text{at low energies}} -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$

hypercharge field strength

photon field strength

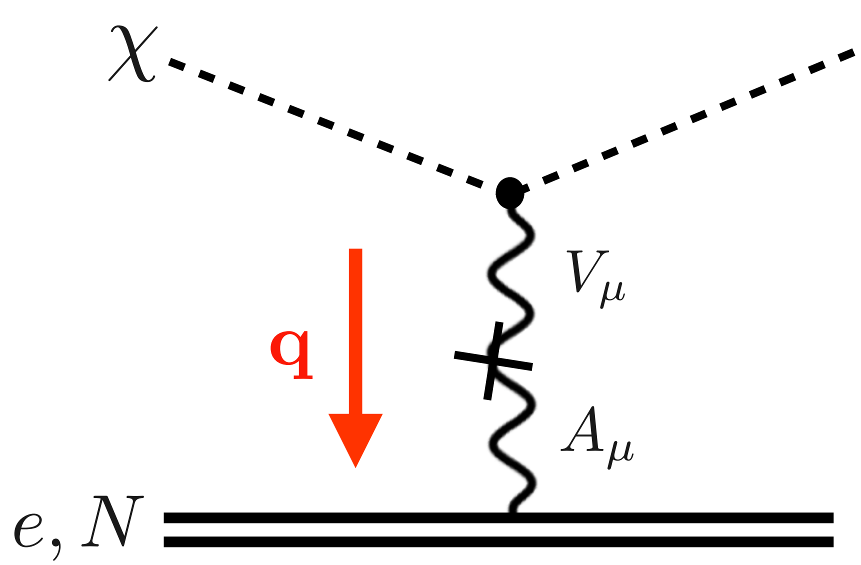
=> two parameter theory: kinetic mixing strength and mass of V

DM Direct Detection

Simple example

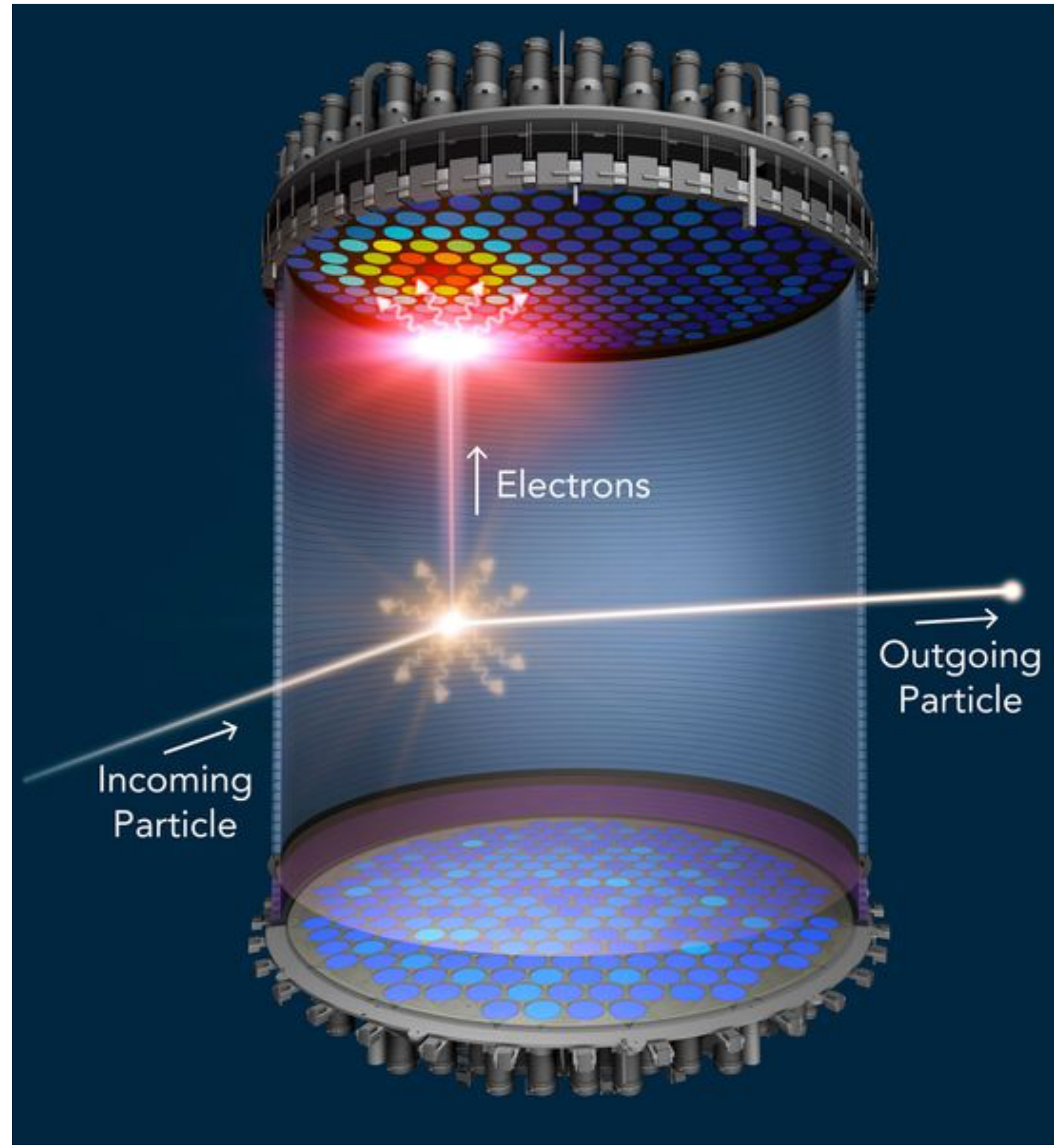
χ is the dark matter

V_μ dark photon is the “mediator”



$m_V \gg |\mathbf{q}|$ point-like interaction

$m_V \ll |\mathbf{q}|$ “millicharged DM”



general detection principles:

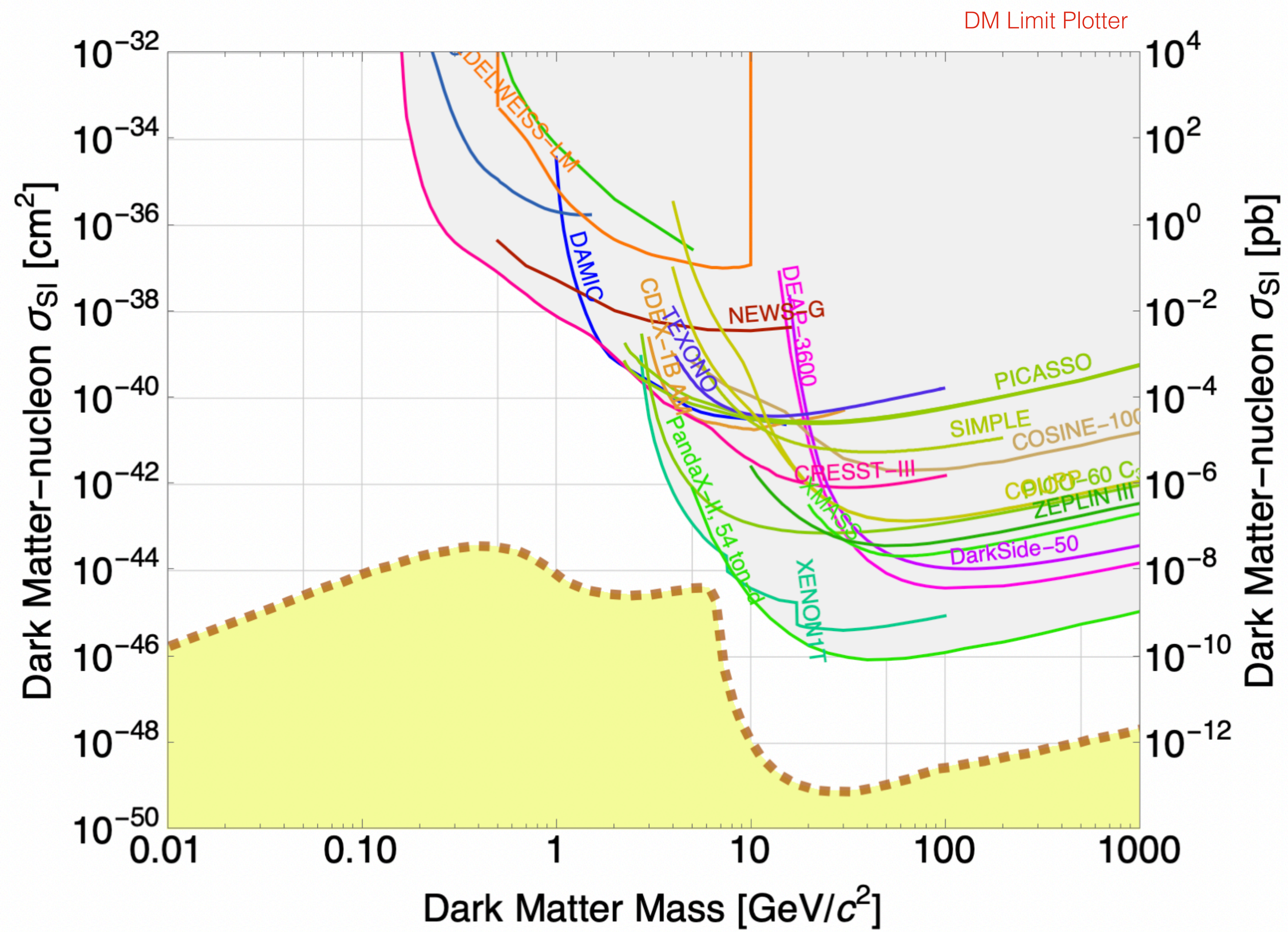
ionziation, scintillation, heat, …

DM Direct Detection

A summary of two decades of effort

Z-mediated

Higgs-mediated

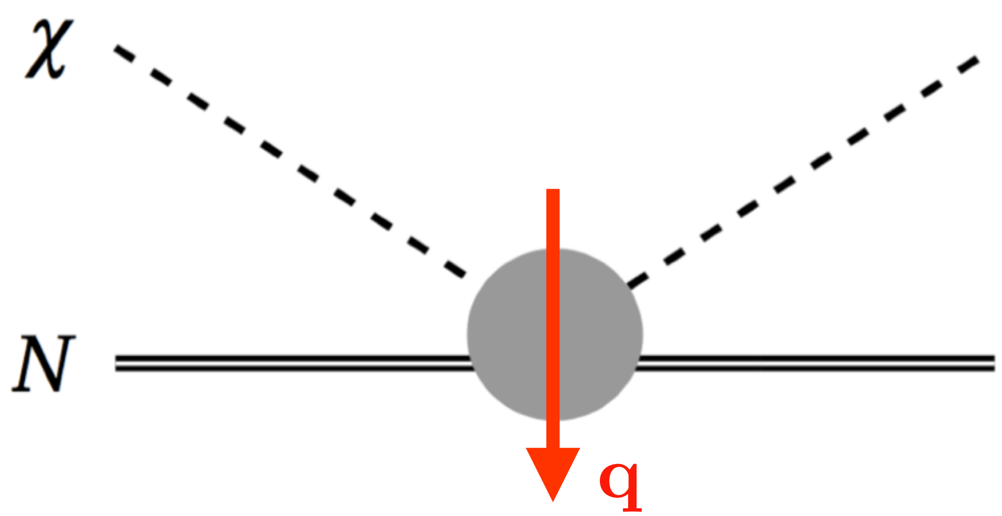


DM Direct Detection

A closer look

Nuclear kinetic recoil energy

$$E_R = \frac{\mathbf{q}^2}{2m_N} = \frac{\mu_N^2 v^2}{m_N}(1 - \cos\theta_*)$$



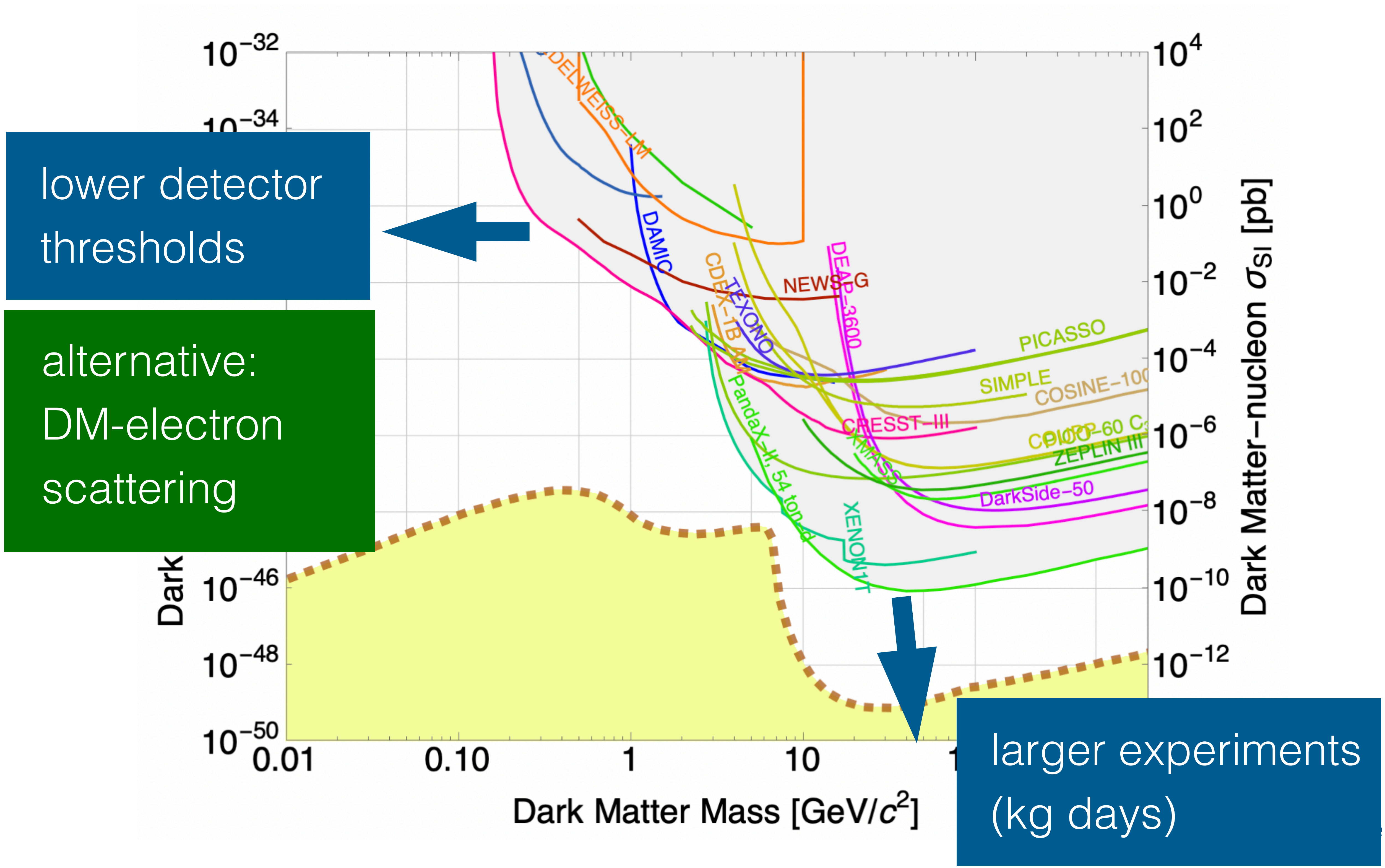
=> A given recoil, demands a minimum relative velocity

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \simeq \left(\frac{E_R}{0.5\,\mathrm{keV}}\right)^{1/2} \frac{1\,\mathrm{GeV}}{m_\chi} \times \begin{cases} 1700\,\mathrm{km/s} & \text{Xenon} \\ 600\,\mathrm{km/s} & \text{Oxygen} \end{cases}$$

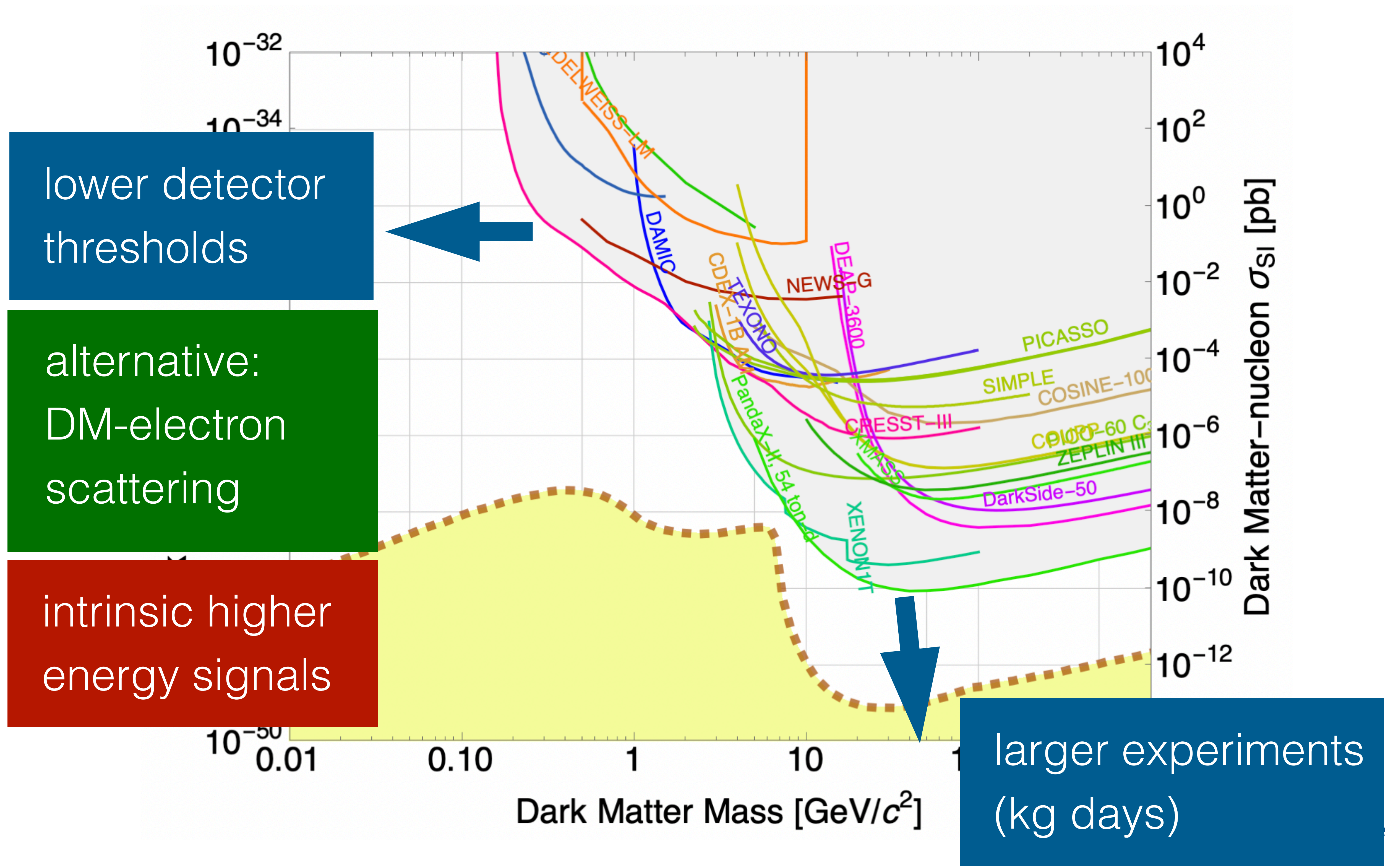
=> if m < 1 GeV, then there are no particles bound to the Galaxy that could induce a 0.5 keV nuclear recoil on a Xenon atom!

"kinematical no-go theorem"

Direct detection low-mass frontier

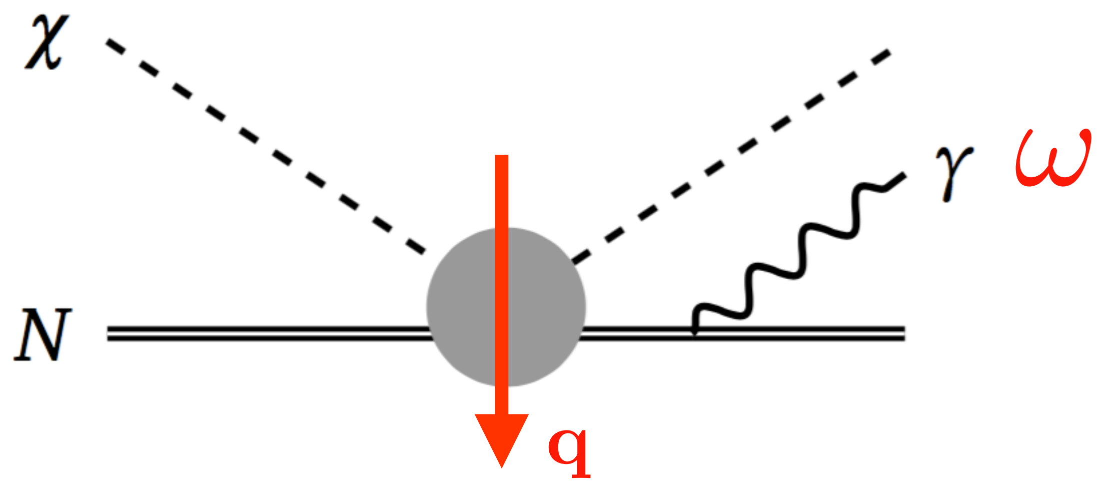


Direct detection low-mass frontier



Gaining access to sub-GeV Dark Matter *through nuclear recoils*

Inelastic channel of photon emission from the nucleus



Maximum photon energy

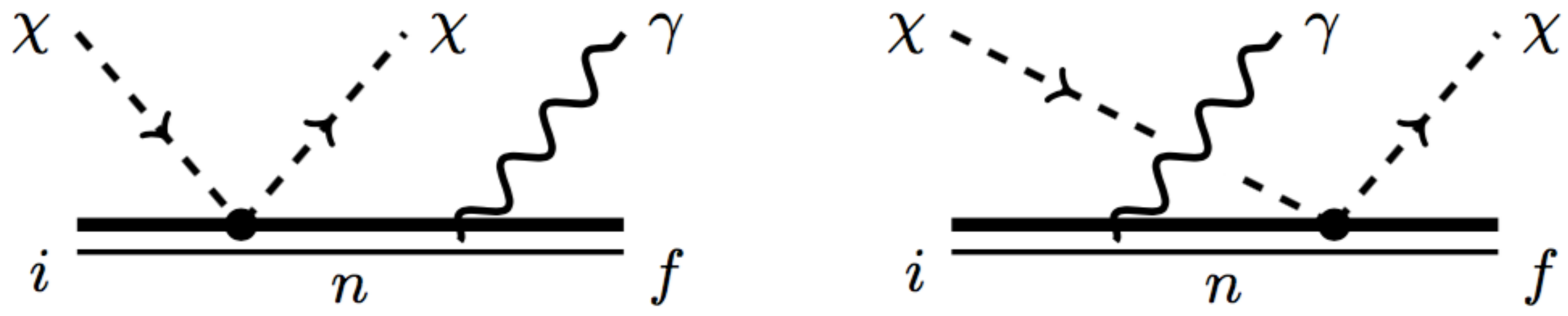
$$\omega_{\rm max} \simeq \mu_N v^2/2 \simeq m_\chi v^2/2$$
$$\simeq 0.5\,{\rm keV}\,\frac{m_\chi}{100\,{\rm MeV}}$$

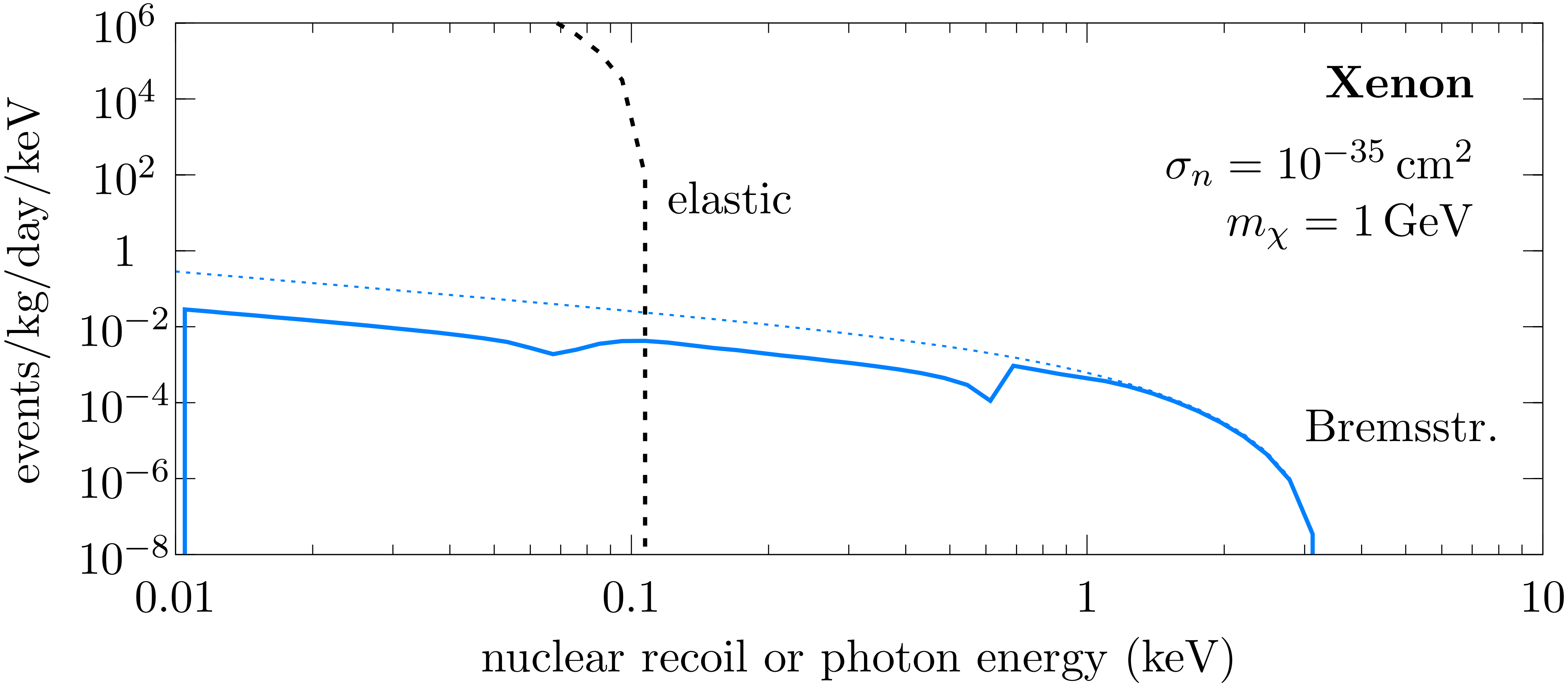
Key I: $E_{R,\rm max} = 4(m_\chi/m_N)\omega_{\rm max} \ll \omega_{\rm max} \quad (m_\chi \ll m_N)$

Key II: 0.5 keV nuclear recoil is easily missed (heat losses),
0.5 keV photon is never missed!

Irreducible signal components

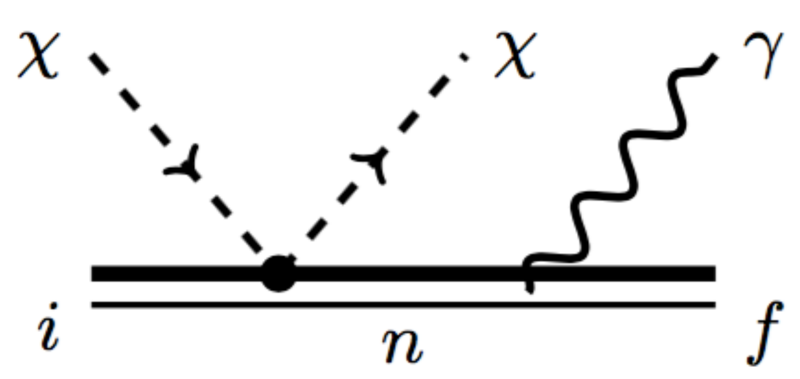
Example Bremsstrahlung

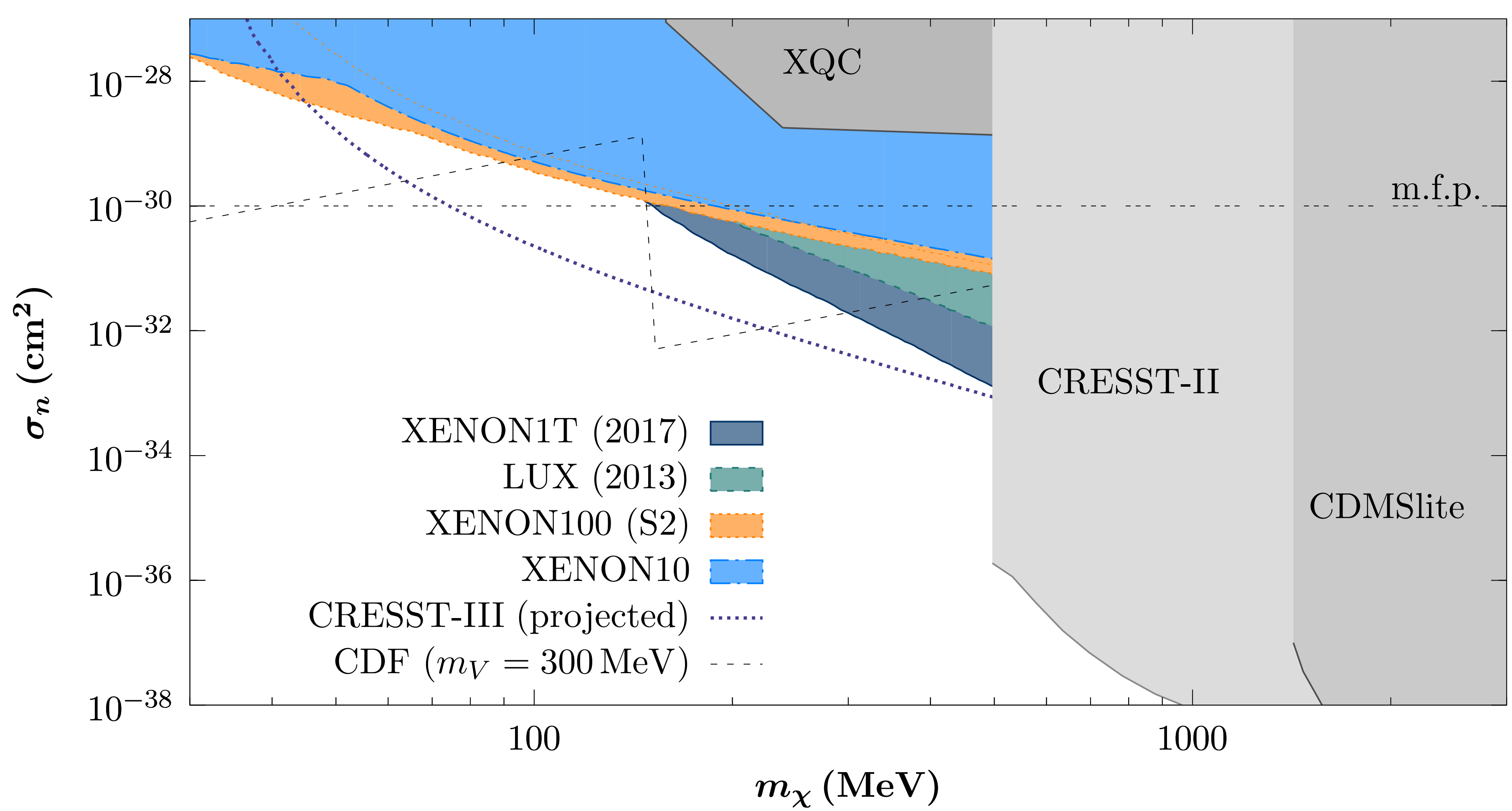




Irreducible signal components

Example Bremsstrahlung

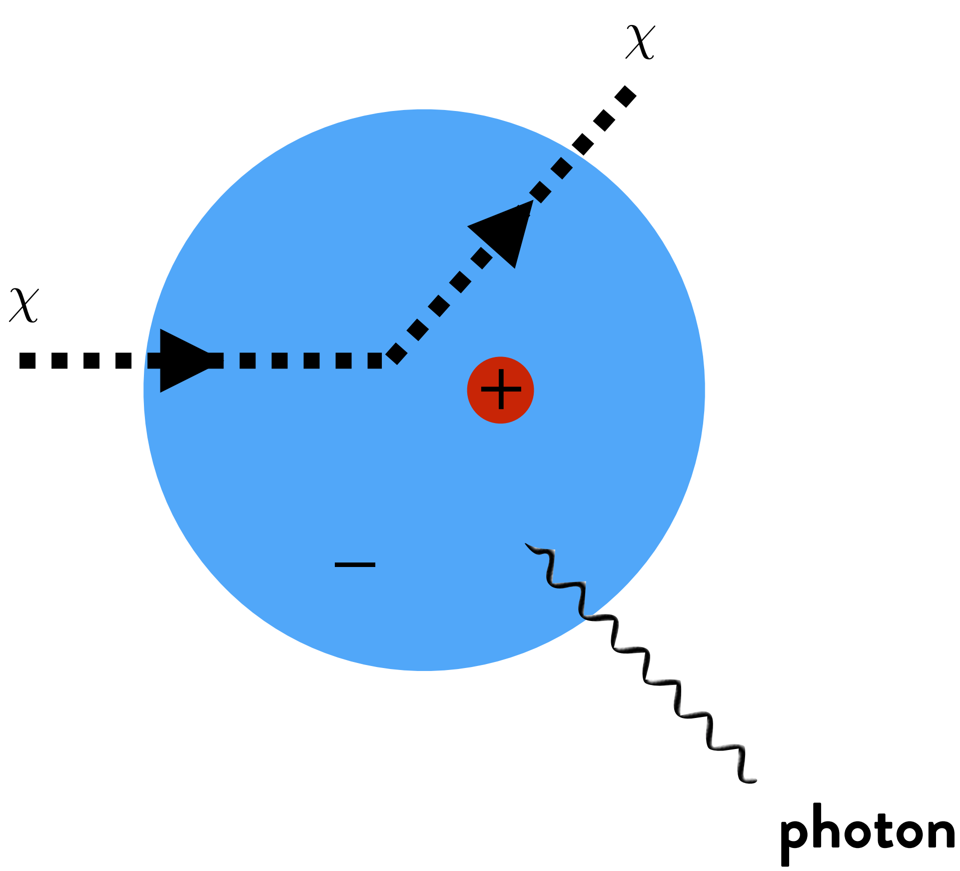




Kouvaris, JP PRL 2016

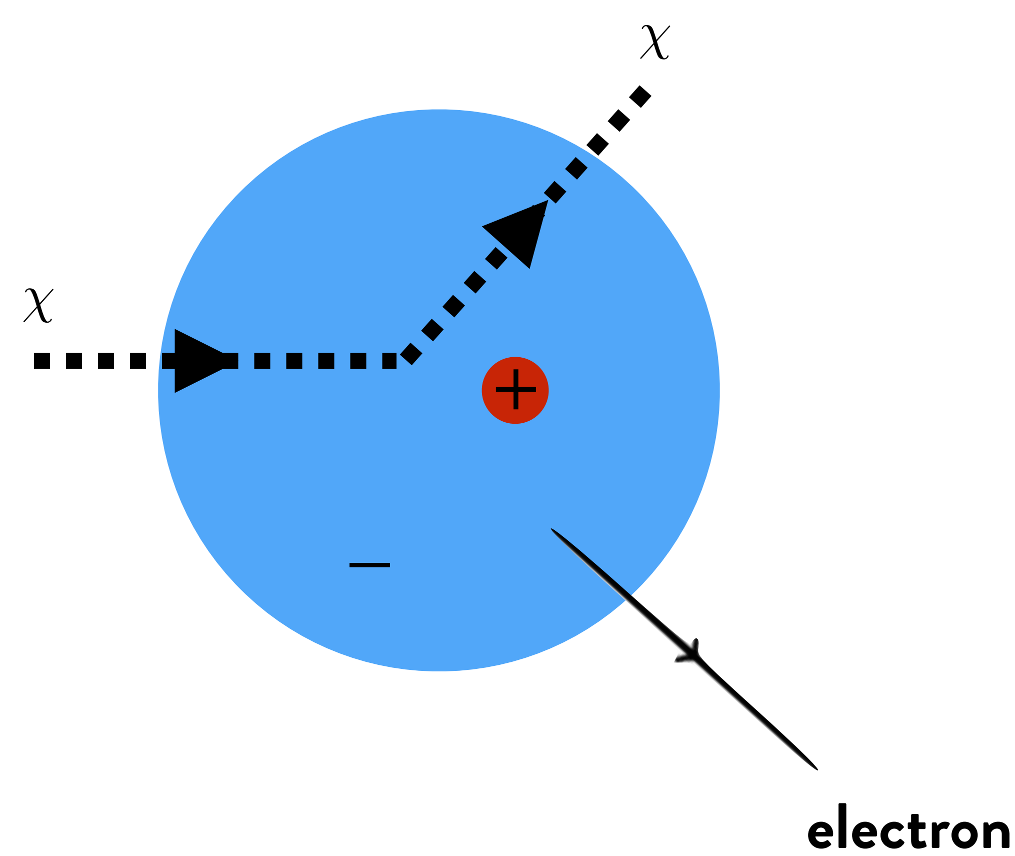
Irreducible signal components

Prompt atomic response following nuclear recoil



Bremsstrahlung

Kouvaris, JP PRL 2016



Migdal-effect

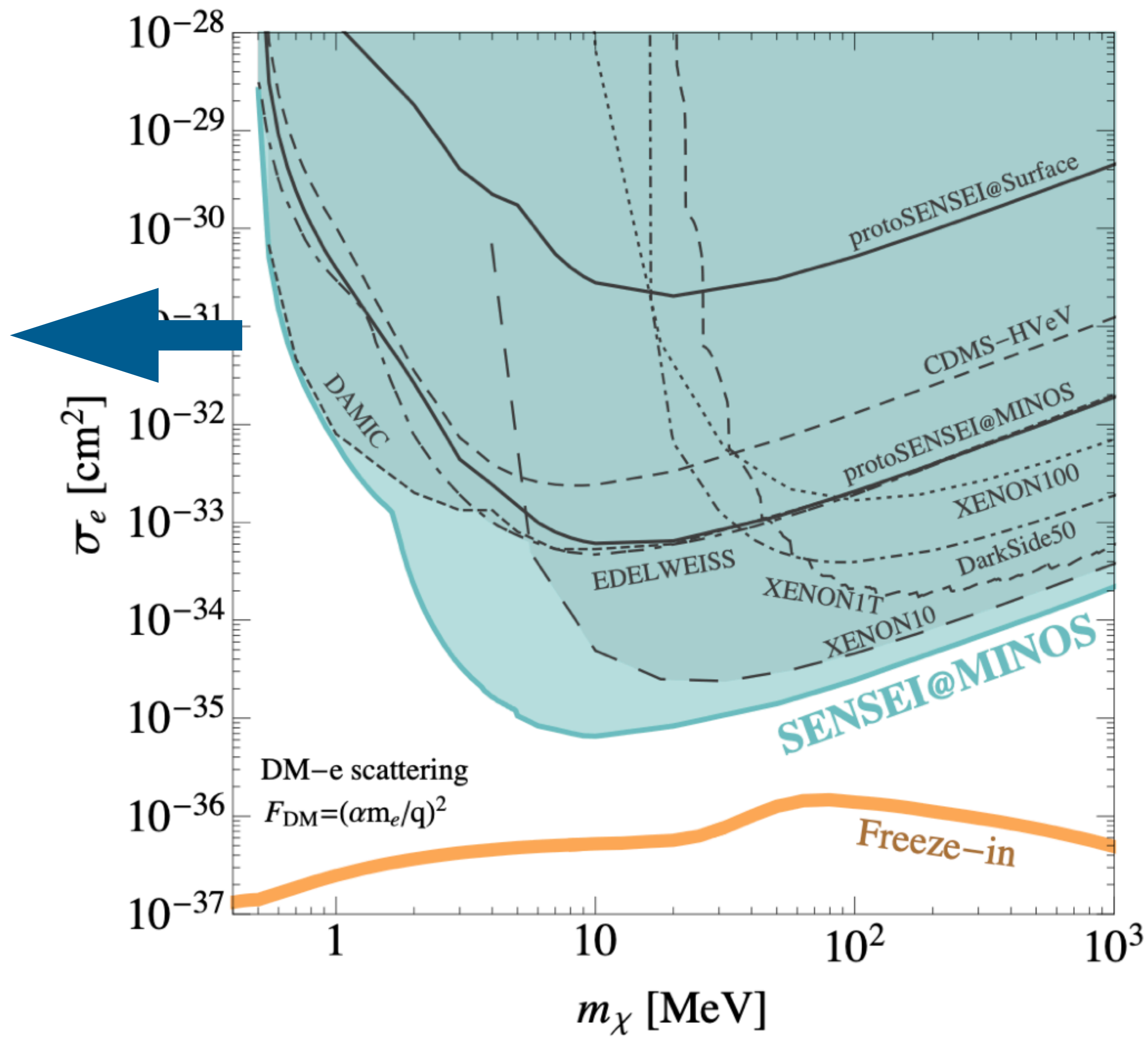
Ibe et al JCAP 2017

Essig, JP, Sholapurkar, Yu PRL 2020

Direct Detection using electrons

alternative technology
(e.g. superconductors)

irreducible higher energy components



E.g. if m < 10 MeV, then there are no particles bound to the Galaxy that could ionize an outer shell Xenon electron

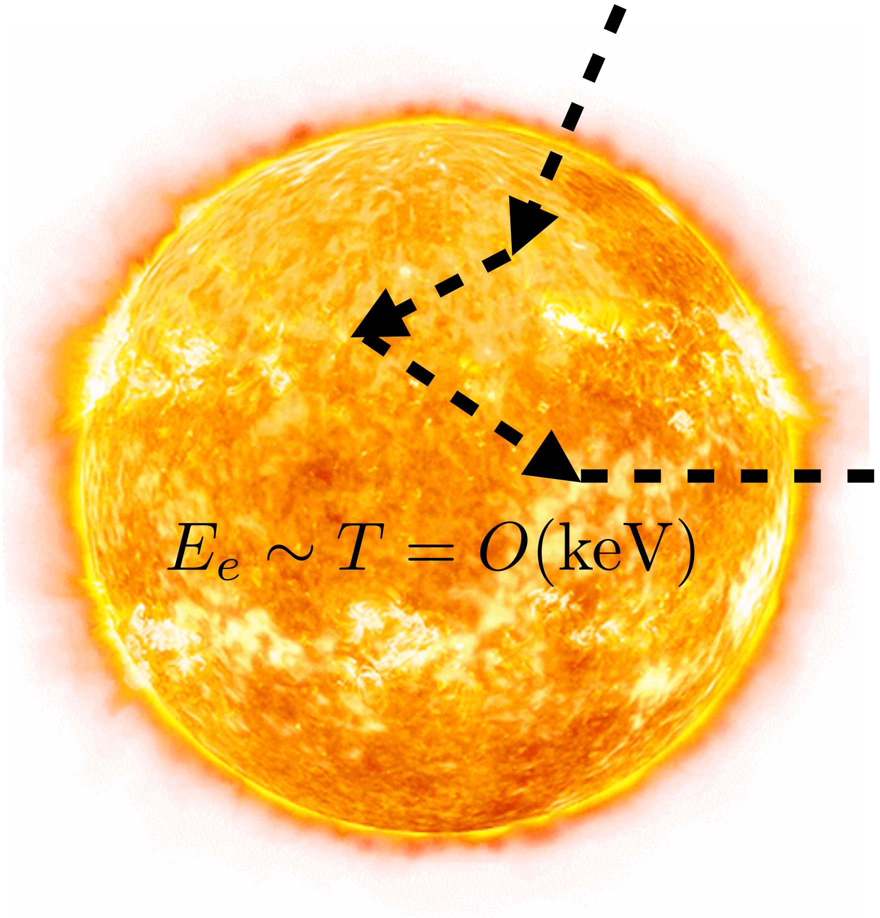
"kinematical no-go theorem" #2

The sun as particle accelerator

Scattering on hot electrons in the solar interior

Galactic Dark Matter $v_{\rm max} \sim 600\,{\rm km/sec}$

Elastic scattering on electrons in the sun's interior lifts DM kinetic energy into (sub-)keV regime



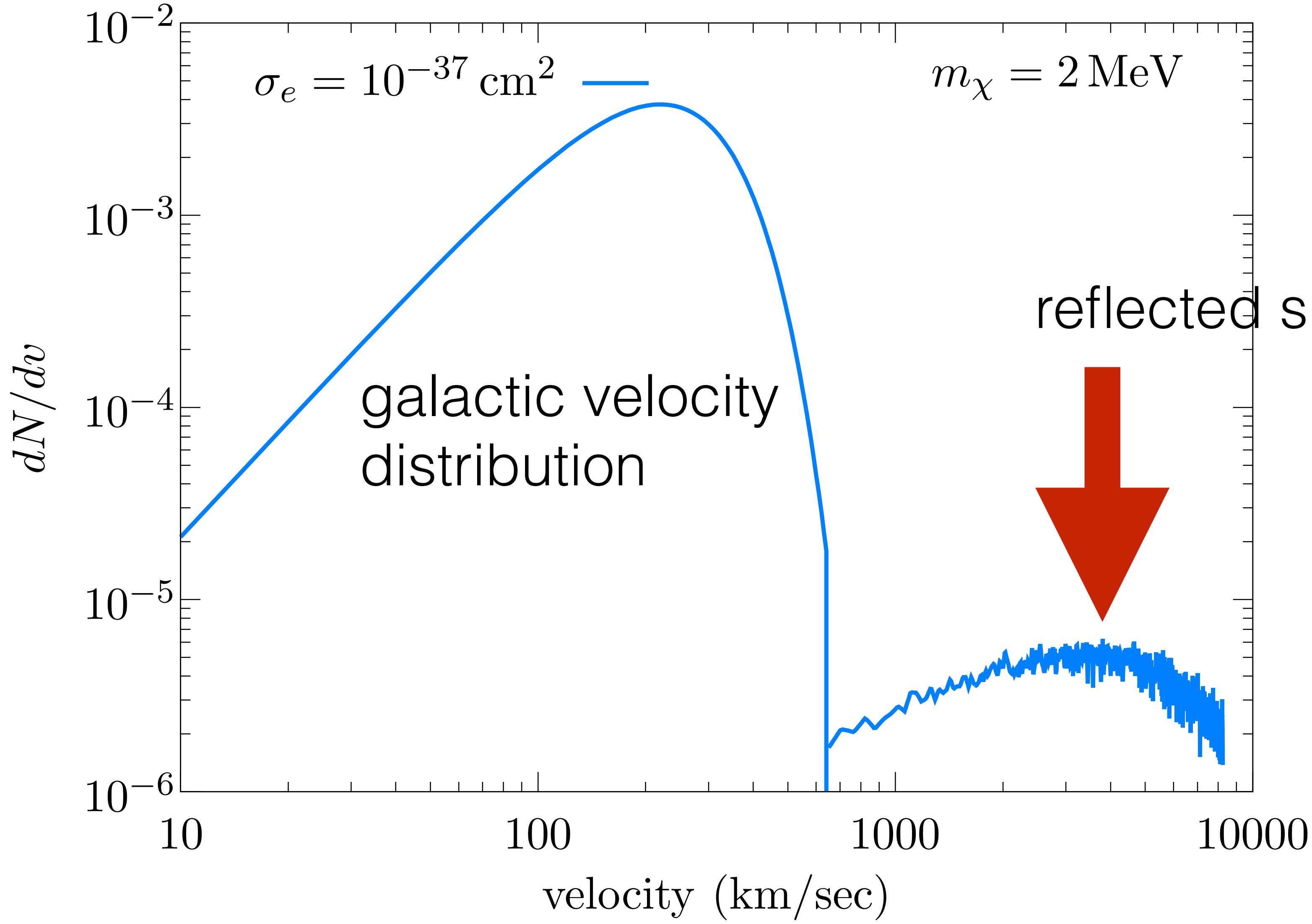
$E_{\rm DM}^{\rm recoil} \sim T$

reflected spectrum

$$v_{\rm max} = \sqrt{2T/m}$$
$$\sim 10^4\,{\rm km/sec} \times \sqrt{1\,{\rm MeV}/m}$$

The sun as particle accelerator

Adding a “hot” tail to the Maxwellian



reflected spectrum from the sun

MC simulation

The sun as particle accelerator

Single scattering limit

mean free path of DM in the sun $l_{\rm fp} = [n_e \langle \sigma_{\rm tot} v_r \rangle]^{-1} \bar{v}_\chi$

probability of scattering $P_s \sim R_{\rm traj}/l_{\rm fp} \sim$

$$\sim \rho_{\rm core}/m_p \times R_{\rm traj} \times \sigma_{\rm tot} \times \frac{\bar{v}_e}{\bar{v}_\chi}$$

$$\sim \frac{\sigma_{\rm tot}}{10^{-38}\ {\rm cm}^2}$$

ballpark number for solar reflection

reflected flux $\frac{d\Phi_{\rm reflected}}{dE_\chi} = \Phi_{\rm halo} \times \frac{F_{A_\rho} A_\rho}{4\pi({\rm A.U.})^2}$ $A_\rho = \pi(4R_\odot)^2,\ \int dE_\chi F_{A_\rho} = 1$

=> solid angle suppression ~ 10^{-4}

Direct Detection of sub-MeV DM

Example model with contact interactions

UV completed through Z' where relic density is set via p-wave annihilation and safe from CMB constraints on energy injection (modulo model dependent $N_{\rm eff}$ contributions)

$$\mathcal{L}_{\rm int} = G_{\chi e} \times (\bar{e}\gamma^{\mu} e)(i\chi^{*}\partial_{\mu}\chi - i\chi\partial_{\mu}\chi^{*})$$

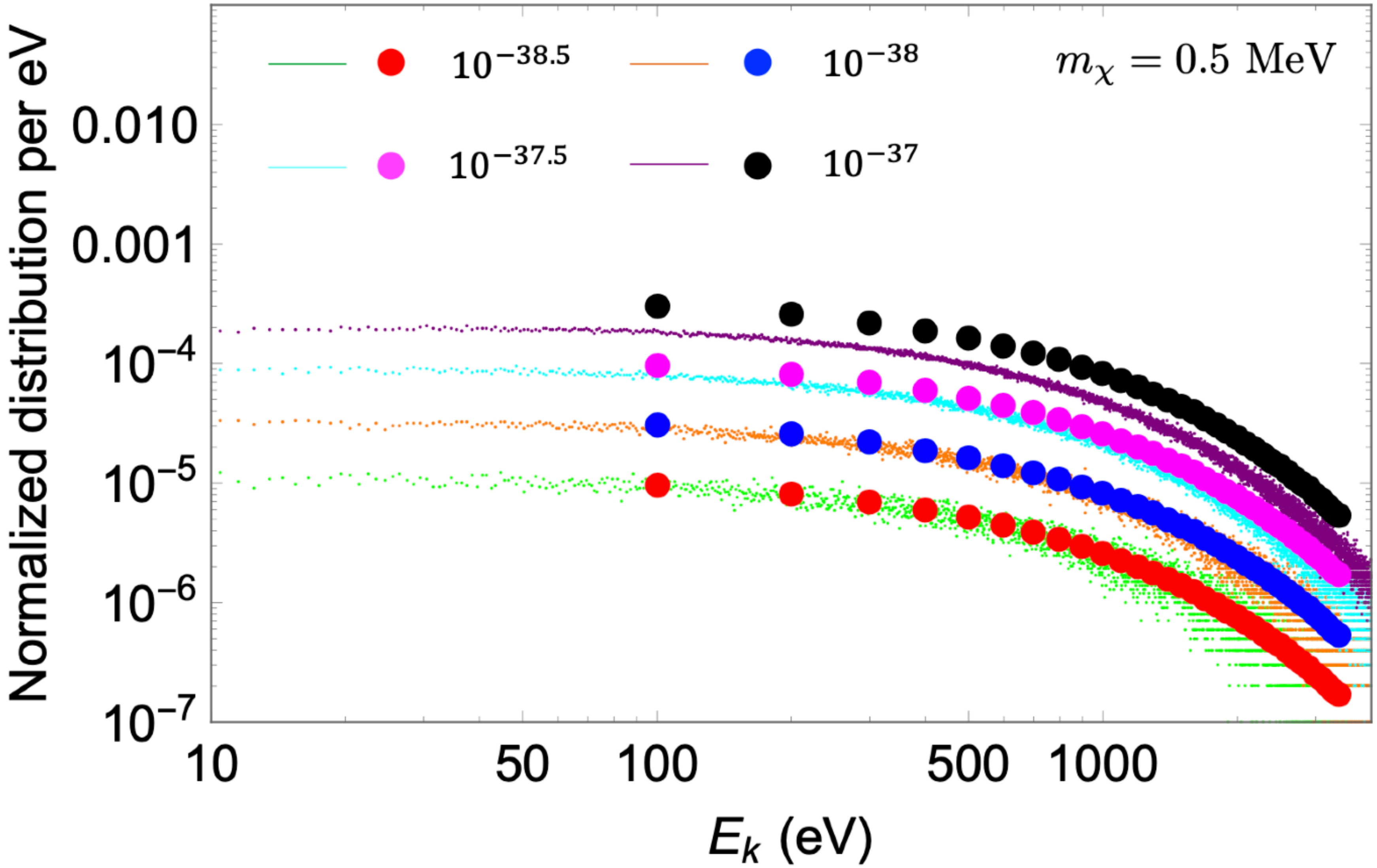
$$\sigma_{\rm ann} v = v^2 \times \frac{G_{\chi e}^2}{12\pi}(m_e^2 + 2m_\chi^2)\sqrt{1 - \frac{m_e^2}{m_\chi^2}}$$

=> relic density requirement points to

$$\sigma_e = \frac{1}{\pi} G_{\chi e}^2 \mu_{\chi,e}^2 \;\; \to \;\; (8{-}9) \times 10^{-35}\,{\rm cm}^2 \;\times\; \frac{2\mu_{\chi,e}^2}{(2m_\chi^2 + m_e^2)v_e}$$

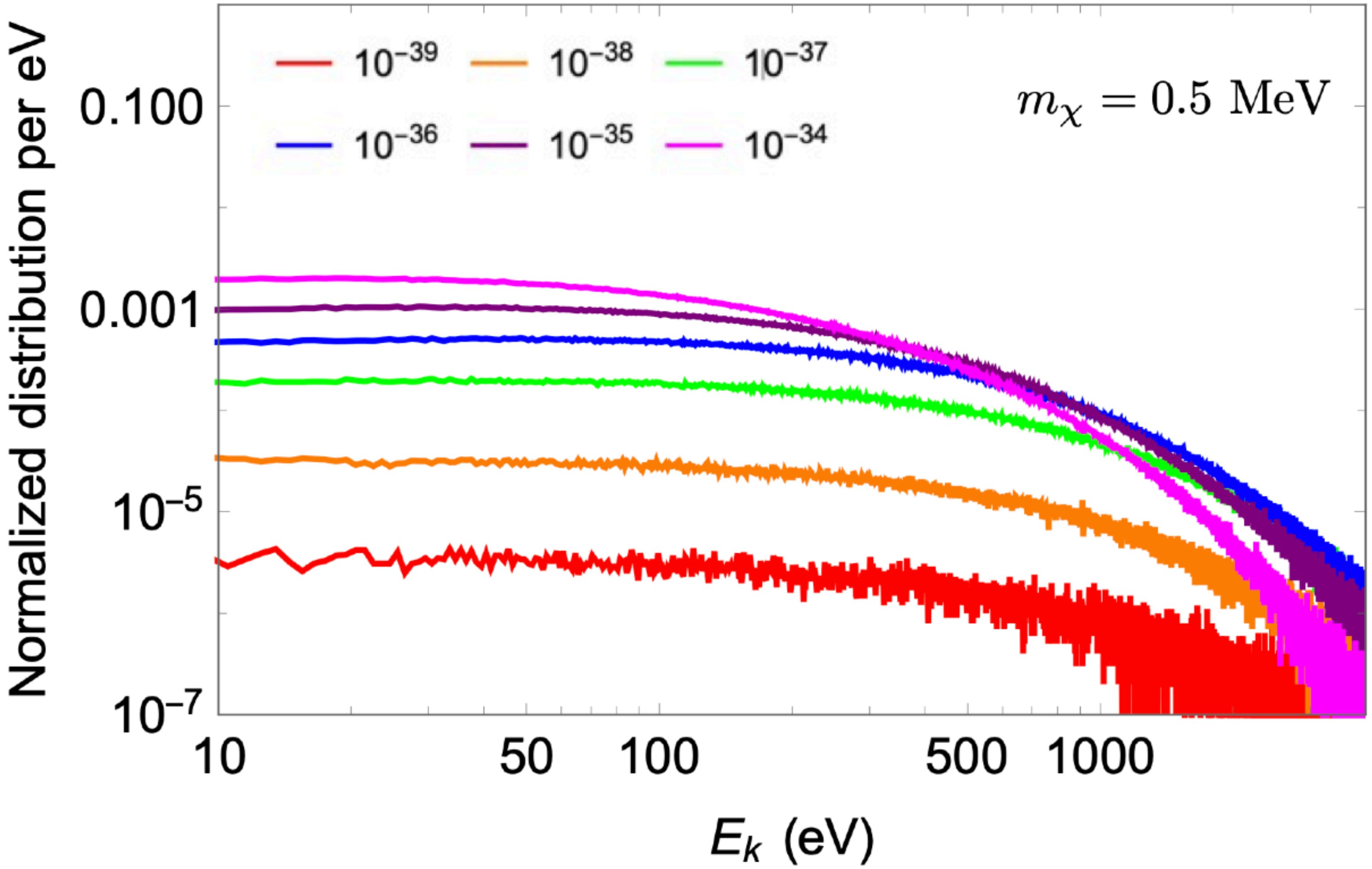
The sun as particle accelerator

Validating the Monte Carlo simulation in the single scattering limit



The sun as particle accelerator

Quantitative results for simulated fluxes



Spectra become softer for increasing cross section => reflection at larger radii

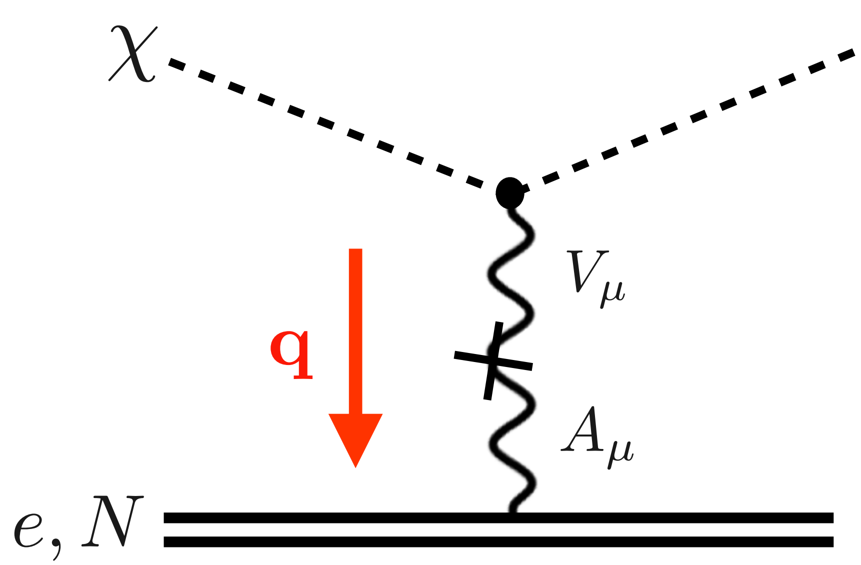
Spectra hardest for when the DM mass equals the electron mass

DM Direct Detection

Simple example

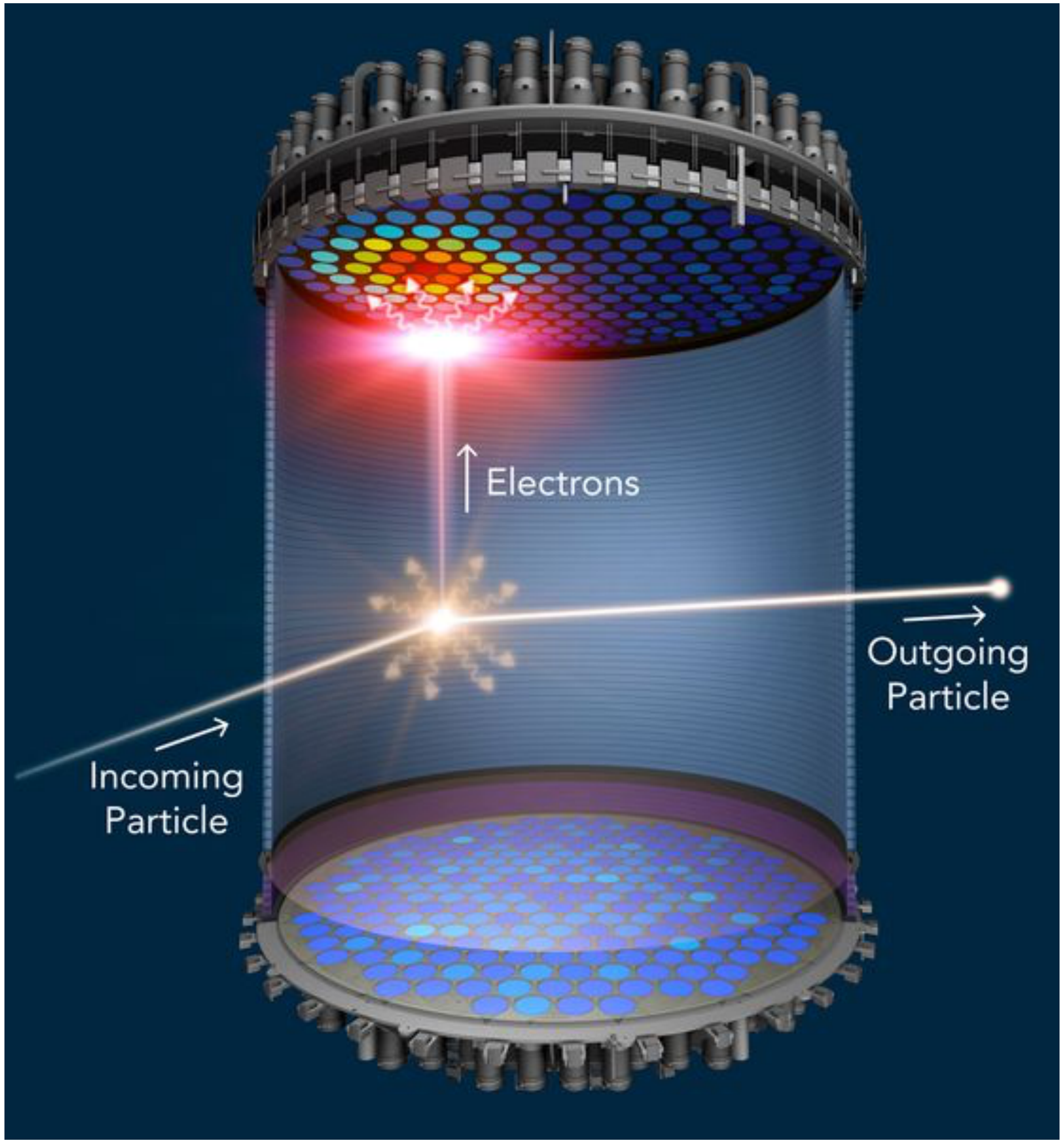
χ is the dark matter

V_μ dark photon is the "mediator"



$m_V \gg |\mathbf{q}|$ point-like interaction

$m_V \ll |\mathbf{q}|$ "millicharged DM"



general detection principles:

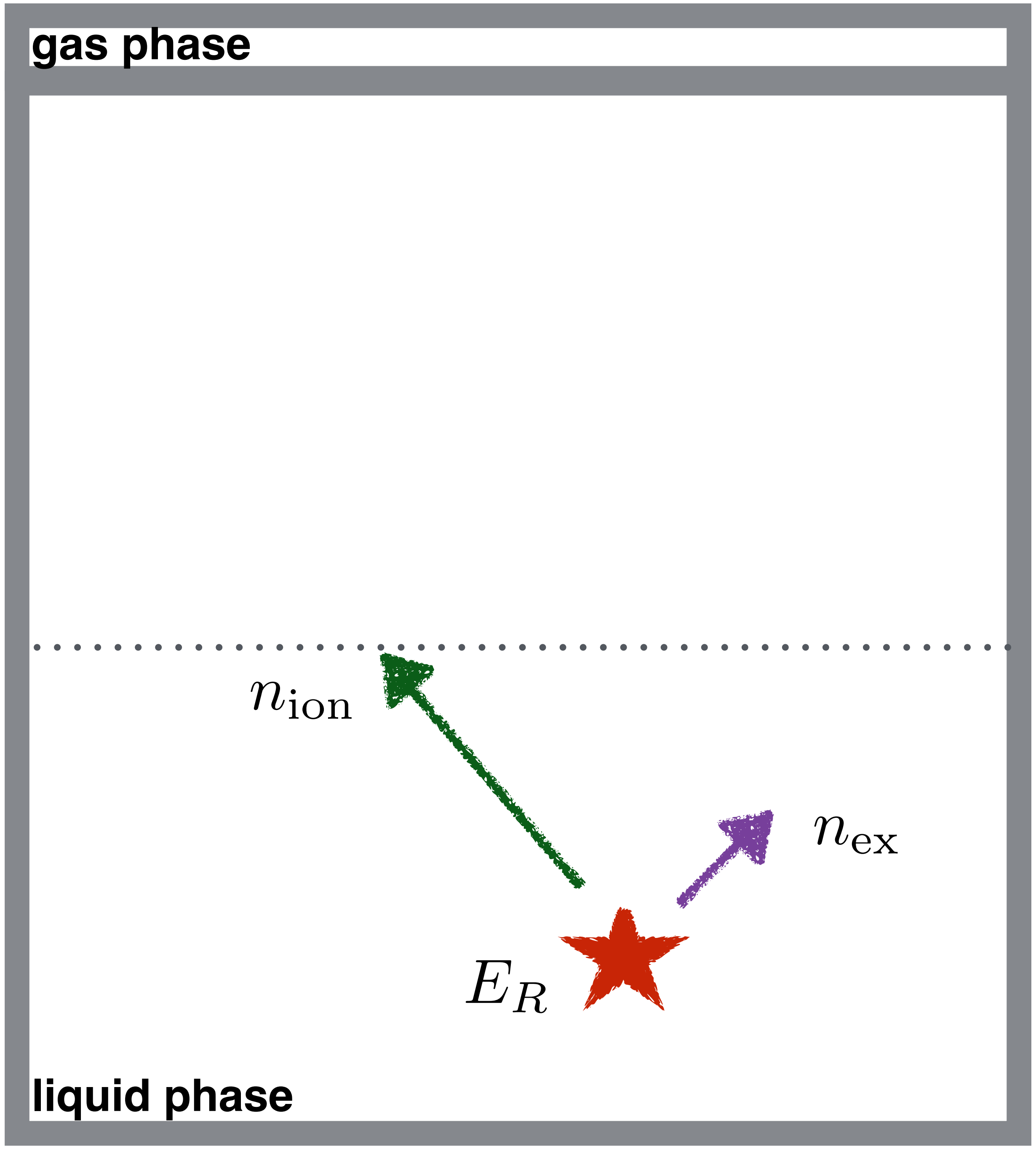
ionziation, scintillation, heat, …

How does an "electron recoil" signal look in a LXE detector?

$$N_Q = \frac{E_R}{W} = n_{\text{ion}} + n_{\text{ex}}$$

$$W \simeq 13.7\,\text{eV} \qquad n_{\text{ex}}/n_{\text{ion}} = \text{few}\,\%$$

Given energy deposition E_R , a number of quanta N_Q is produced, distributed in electron-ion pairs and excited atoms n_{ex}

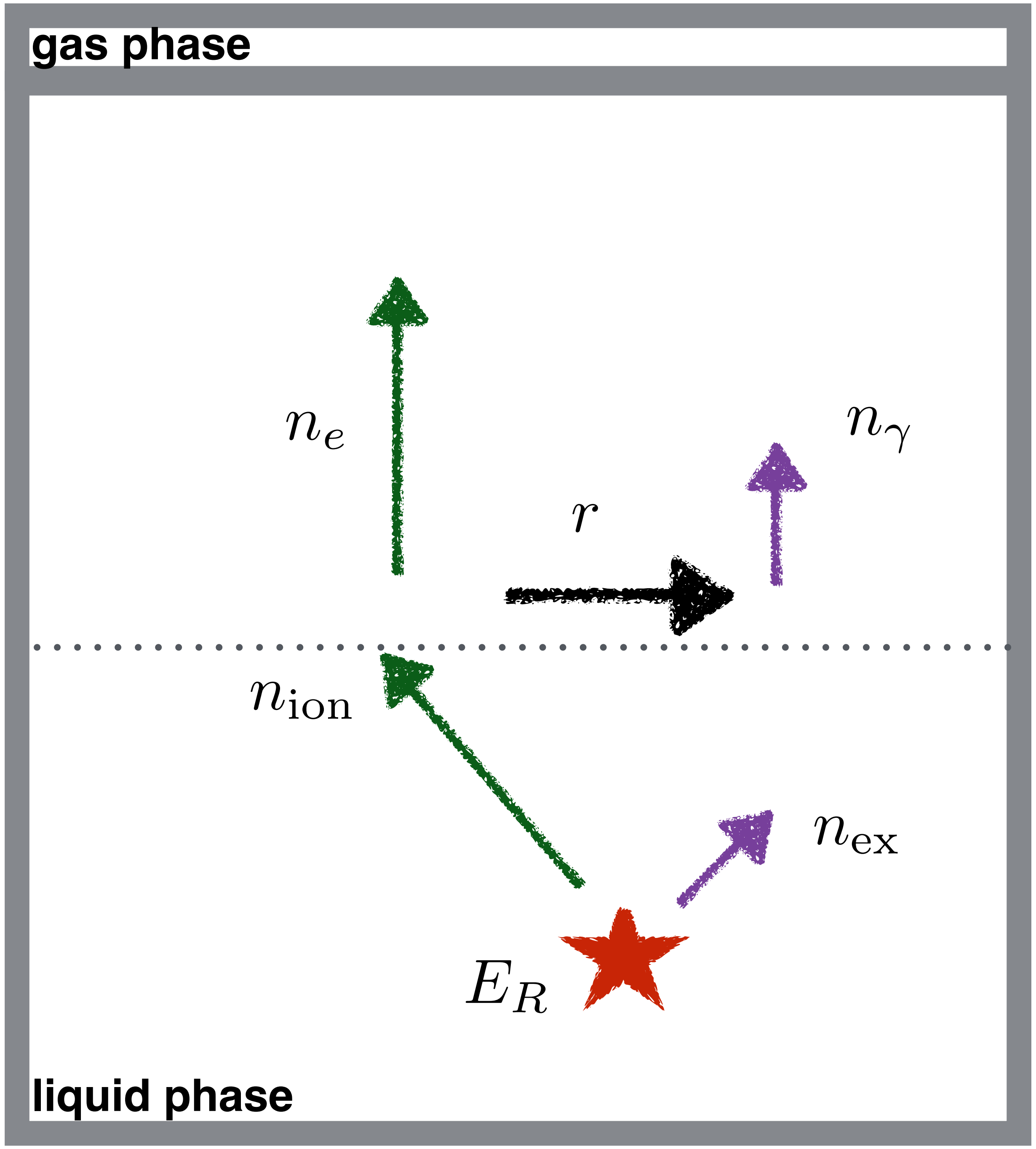


How does an “electron recoil” signal look in a LXE detector?

$$N_Q = \frac{E_R}{W} = n_{\rm ion} + n_{\rm ex}$$
$$= n_\gamma + n_e$$

$$n_e = n_{\rm ion}(1-r), \quad n_\gamma = n_{\rm ion} r + n_{\rm ex}$$

Observable: de-excitation photons from initial and recombined excitons n_γ and electrons that escape recombination n_e



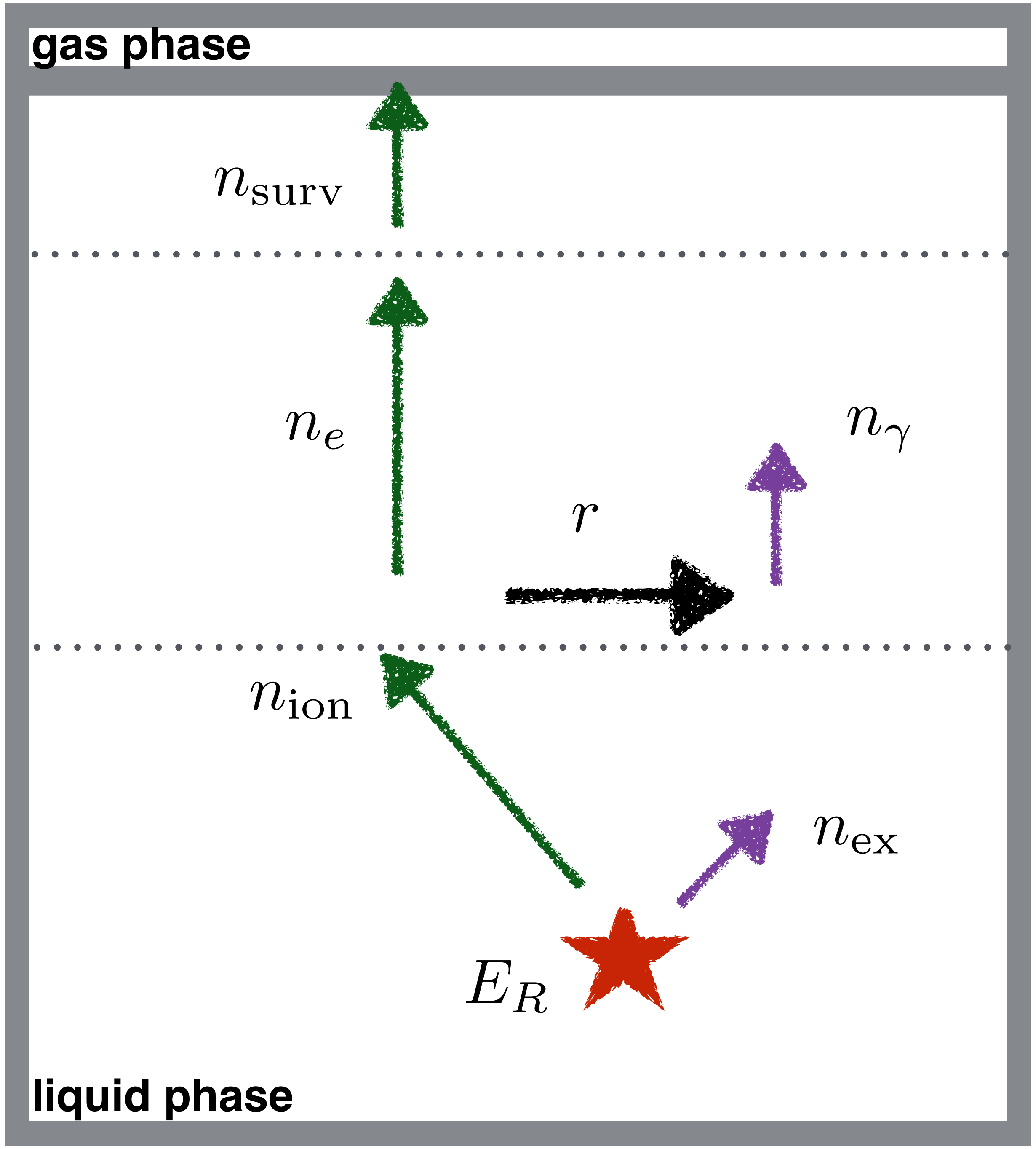
How does an "electron recoil" signal look in a LXE detector?

$$p_{\rm surv} \simeq \exp\left(-\frac{\Delta z}{\tau v_d}\right)$$

$$v_d \simeq 1.7 \mathrm{mm}/\mu\mathrm{s} \qquad \tau > 1\,\mathrm{s}$$

Electrons are drifted in the electric field towards the liquid-gas interface; depending where they are created, attenuation occurs

$$p_{\rm surv} \sim 0.6 - 0.9$$

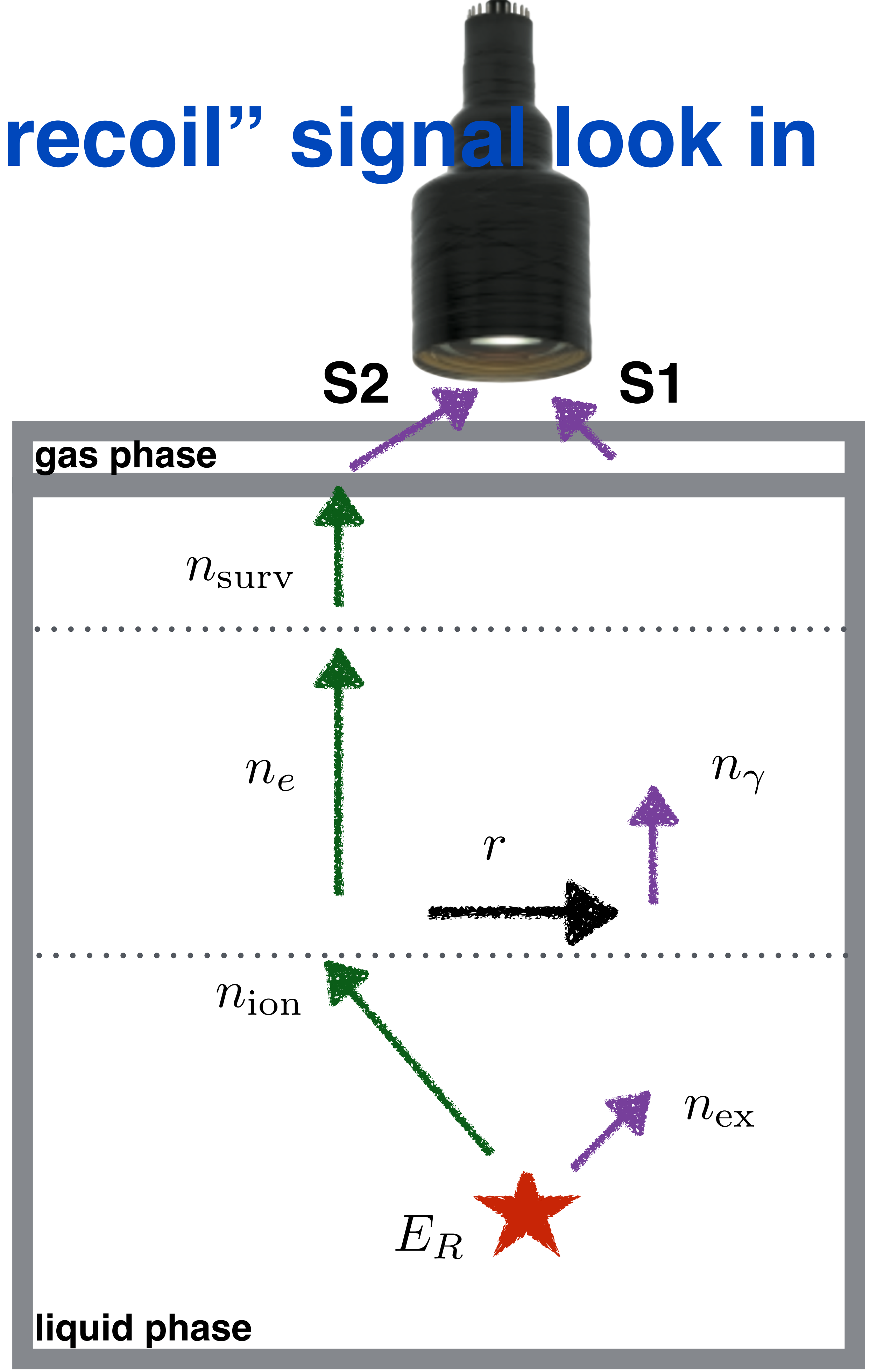


How does an “electron recoil” signal look in a LXE detector?

$$N_Q = n_{\text{ion}} + n_{\text{ex}}$$
$$= n_\gamma + n_e$$
$$= \frac{S1}{g_1} + \frac{S2}{g_2}$$

$$g_1 \simeq 0.1, \quad g_2 \simeq 10 - 50$$

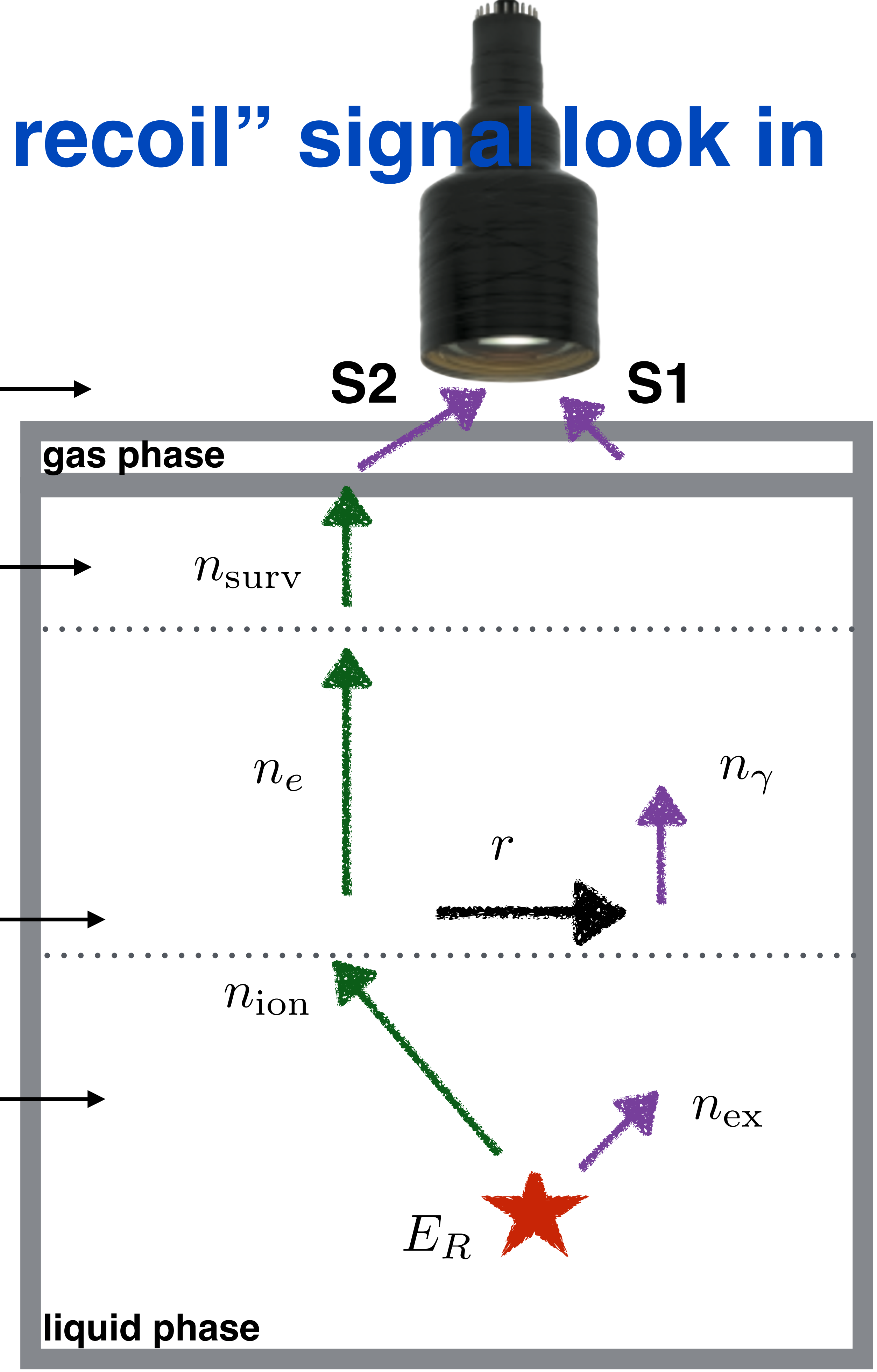
An electron reaching the liquid-gas interface creates about O(10) PE (S2); it takes on average 10 scintillation photons to collect 1 PE (S1)



How does an “electron recoil” signal look in a LXE detector?

detector specific
- fluctuates →
- fluctuates →

LXE universal (given E-field)
- fluctuates →
- →



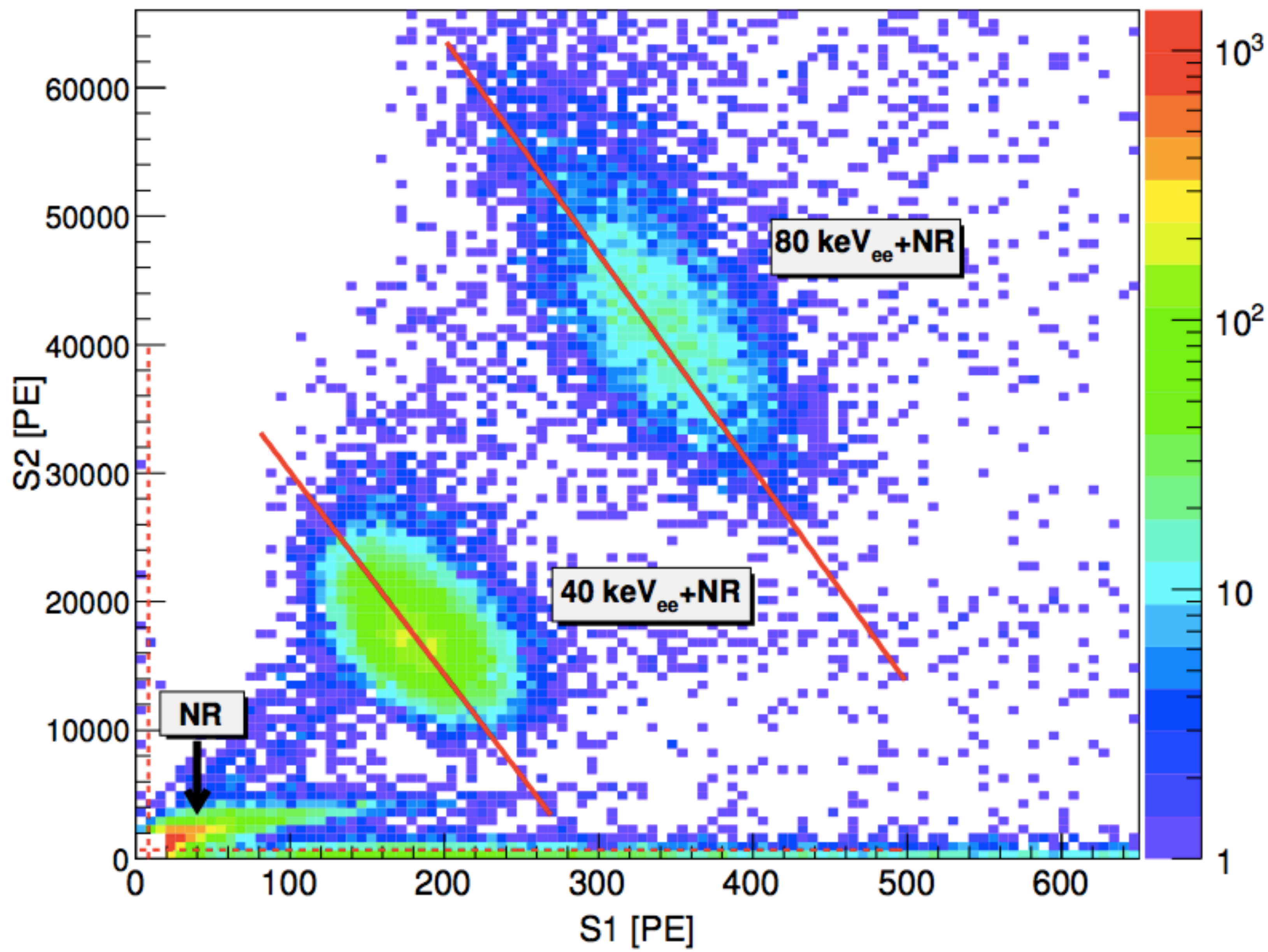
=> model PDF(S1,S2 | E_{dep})

How does an "electron recoil" signal look in a LXE detector?

e.g. PandaX

$$N_Q = n_{\text{ion}} + n_{\text{ex}}$$
$$= n_\gamma + n_e$$
$$= \frac{S1}{g_1} + \frac{S2}{g_2}$$

note the anti-correlation between S1 and S2



How does an “electron recoil” signal look in a LXE detector?

S2-only search

PDF $$P(S2|E_R) = \sum_{n_e^{\rm surv}} \sum_{n_e} P(S2|n_e^{\rm surv}) P(n_e^{\rm surv}|n_e) P(n_e|\langle n_e \rangle)$$

For example: $$P(n_{e,\gamma}|\langle n_{e,\gamma}\rangle) = \mathrm{binom}(n_{e,\gamma}|N_Q, f_{e,\gamma})$$

$$\langle n_e \rangle = E_{\rm dep.} Q_y$$ with charge yield Qy measured or modelled

$$P(n_e^{\rm surv}|n_e) \simeq \langle p_{\rm surv} \rangle = 0.8$$

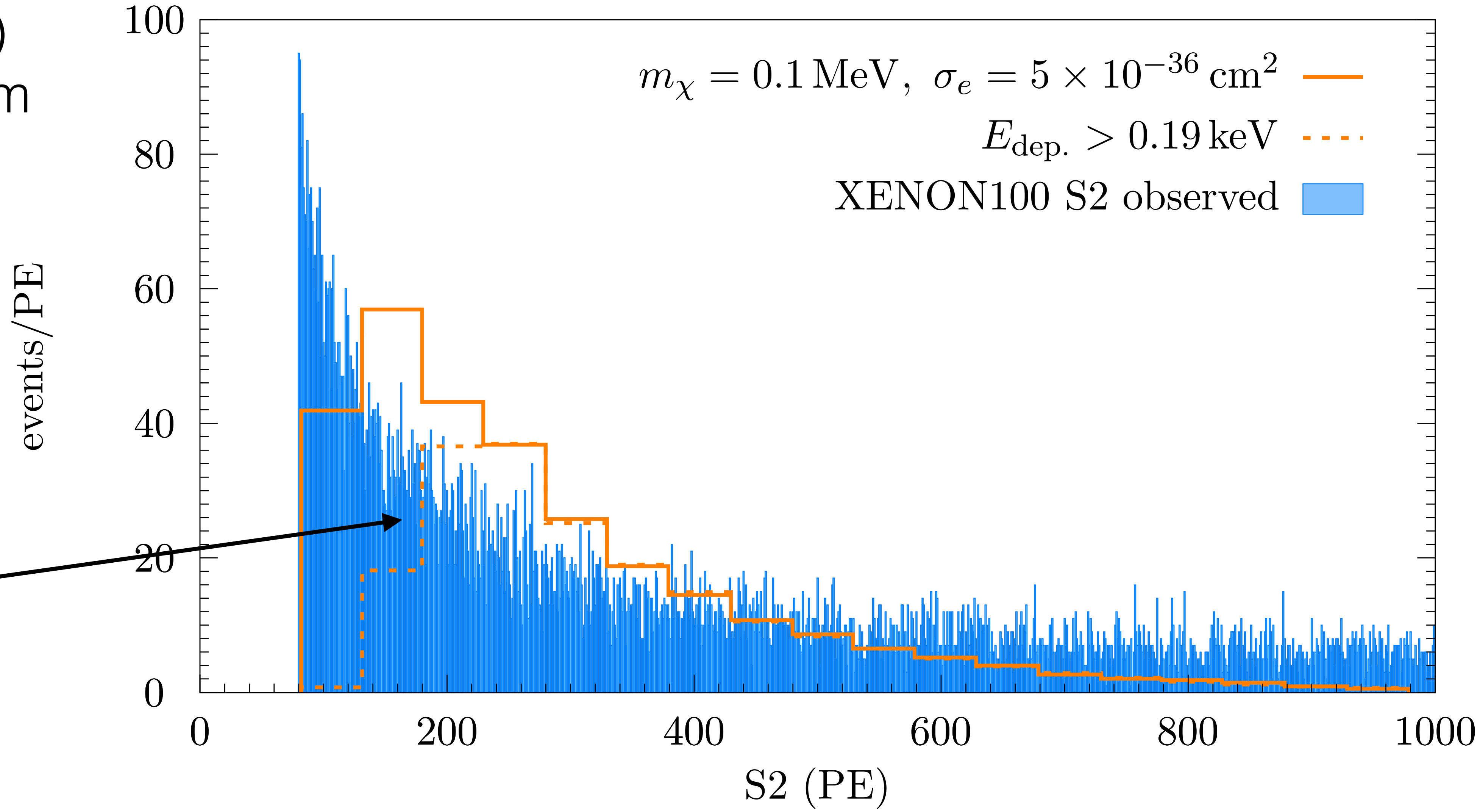
$$P(S2|n_e^{\rm surv}) = \mathrm{gauss}(S2|g_2 n_{e^{\rm surv}}, \sigma_{S2})$$

Experimental rate: $$\frac{dR}{dS2} = \varepsilon(S2) \int dE_R \; P(S2|E_R) \frac{dR}{dE_R}$$

S2 only spectrum

Example XENON100

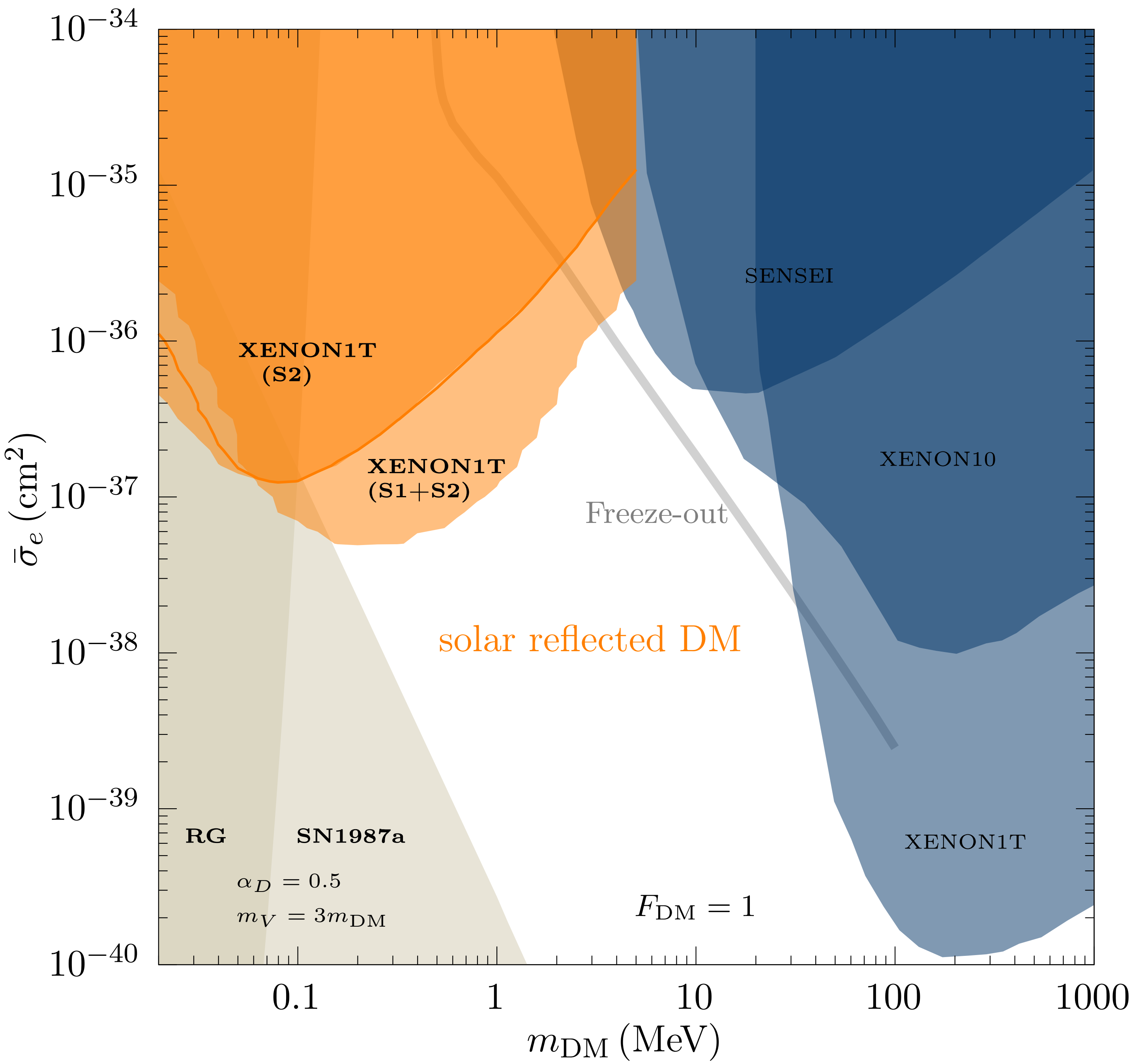
XENON100 (2016)
ionization spectrum



for expt. limits:
demand minimum
deposited energy
of 0.19 keV
=> data driven
approach

Solar Reflection of DM

Contact interactions with electrons



An, Pospelov, JP, Ritz PRL 2018

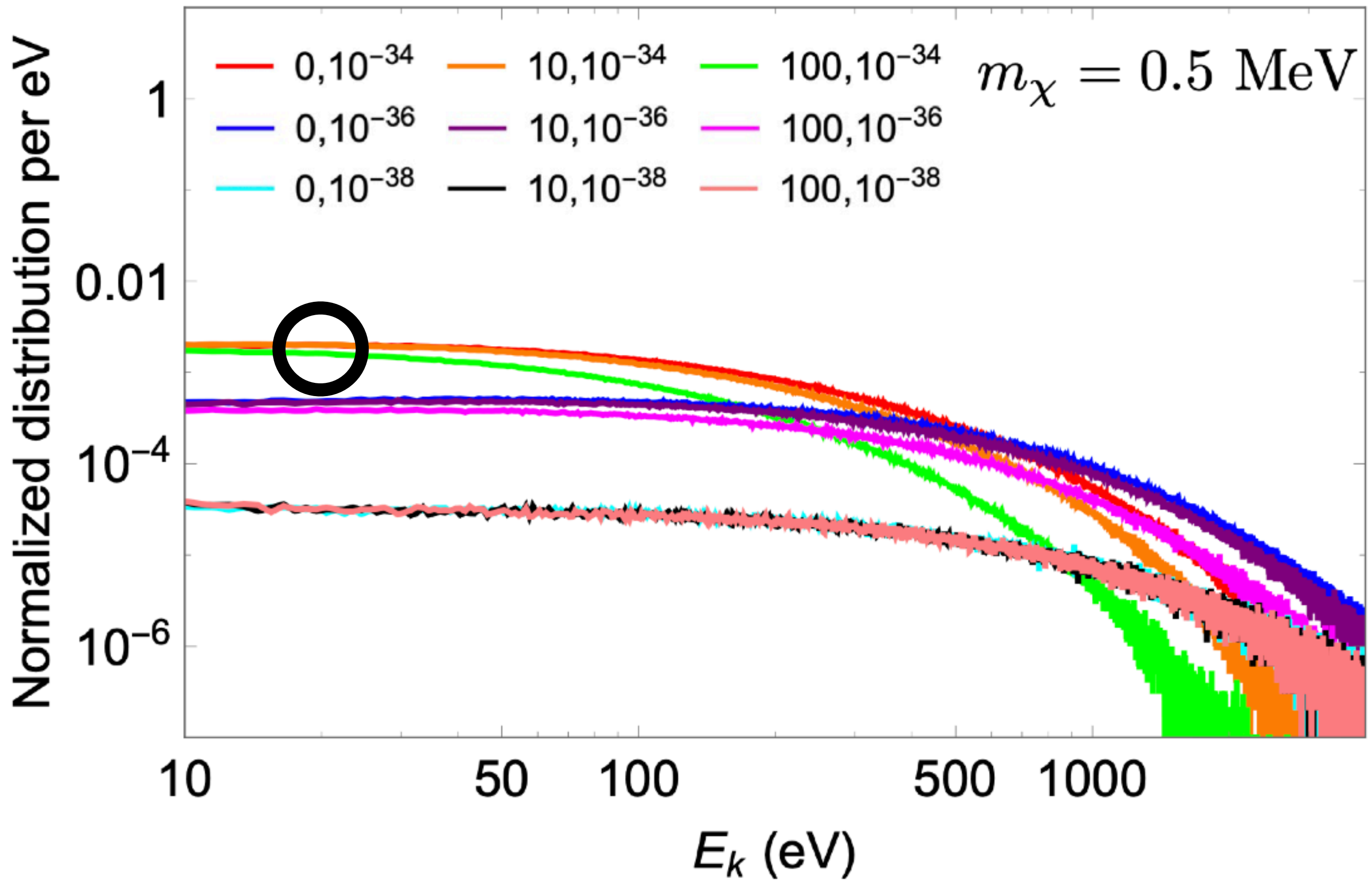
An, Nie, Pospelov, JP, Ritz PRD 2021

Solar Reflection of DM

Role of ions?

$m_\chi \ll m_{\text{nucleus}}$ collisions with ions only change direction but not energy

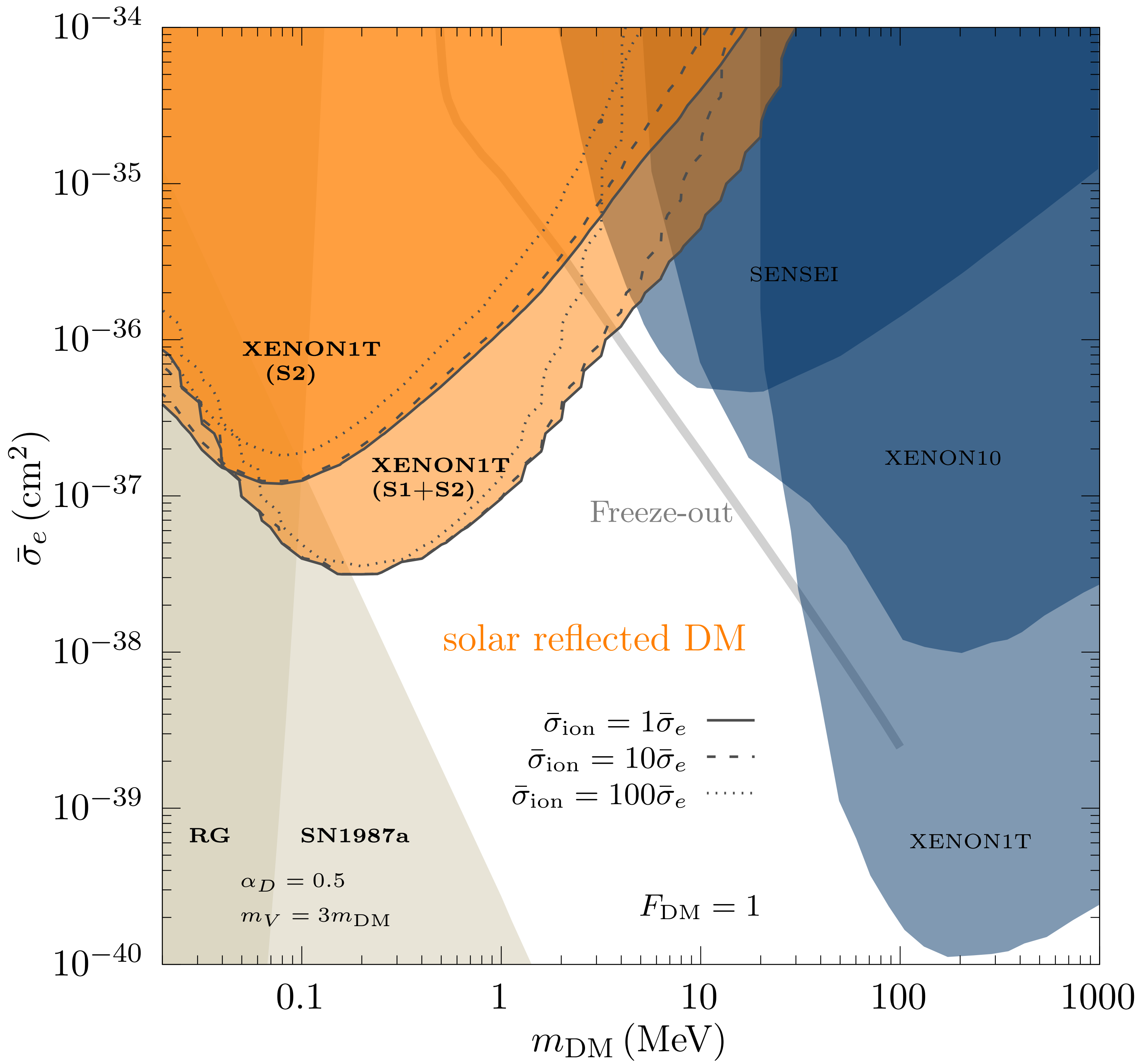
2 options: either ions shield the hot solar core from DM, or they may turn around DM that has already entered and increase chance of further upscattering



=> ions shield the core

Solar Reflection of DM

Role of ions

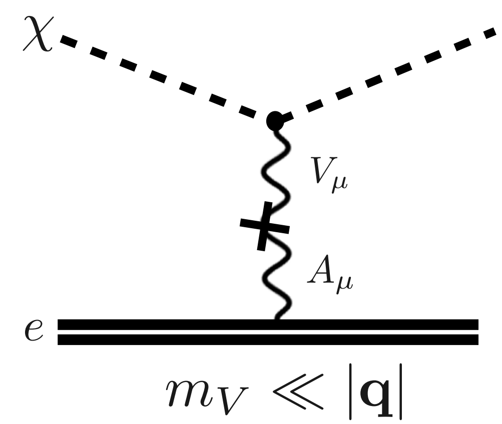


An, Pospelov, JP, Ritz PRL 2018

An, Nie, Pospelov, JP, Ritz PRD 2021

Solar Reflection of DM

Millicharged DM



Difficult/expensive to treat because of long-range interactions

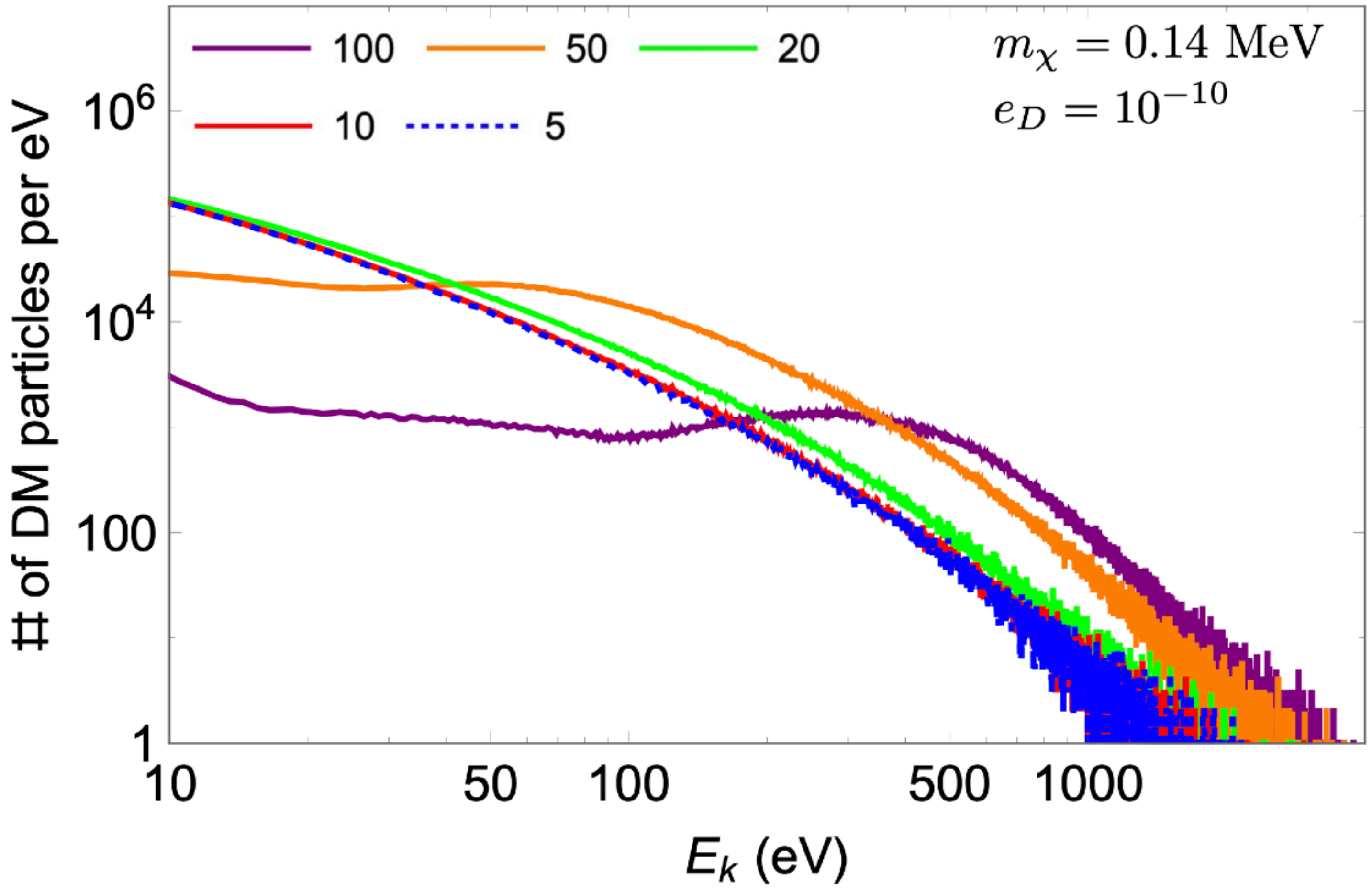
=> forward scattering biased; eventually "Debye-screened

2 effects:

"hard" large-angle scatterings accelerate DM;

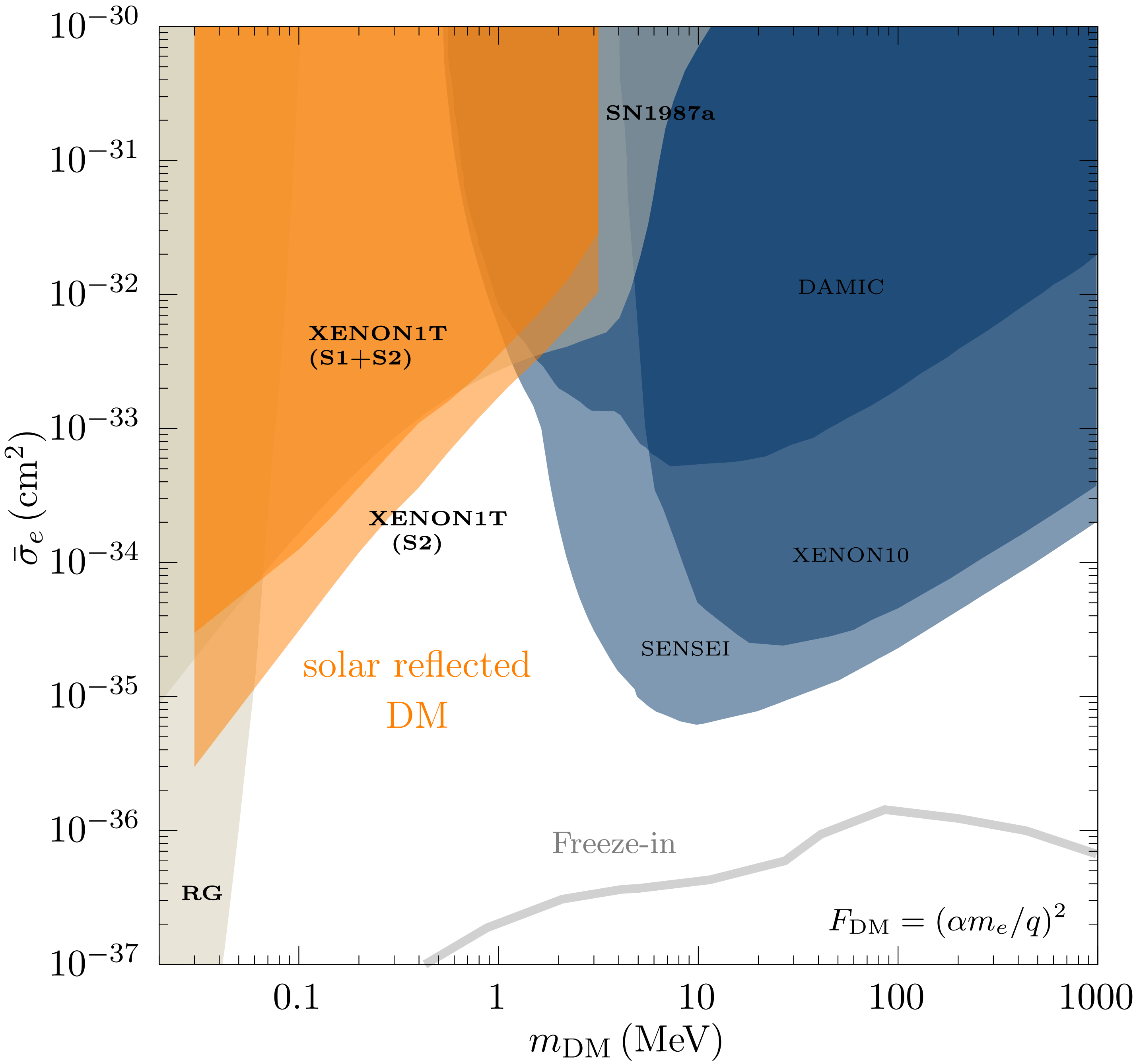
"soft" small-angle scatterings effectively friction/viscosity

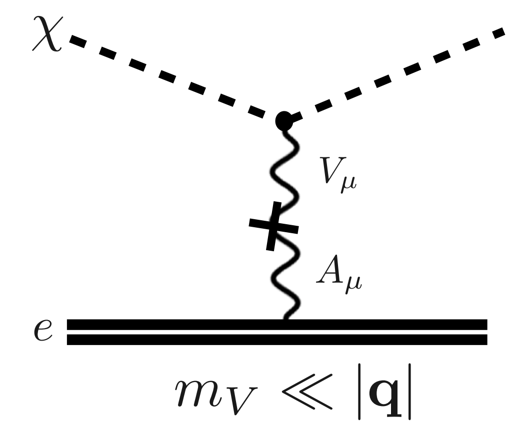
$$x_q = \frac{q}{\sqrt{m_e T}} = \frac{\Delta v_1 m_\chi}{\sqrt{m_e T}} > \frac{\zeta v_1 m_\chi}{\sqrt{m_e T}}$$



Solar Reflection of DM

Millicharged DM



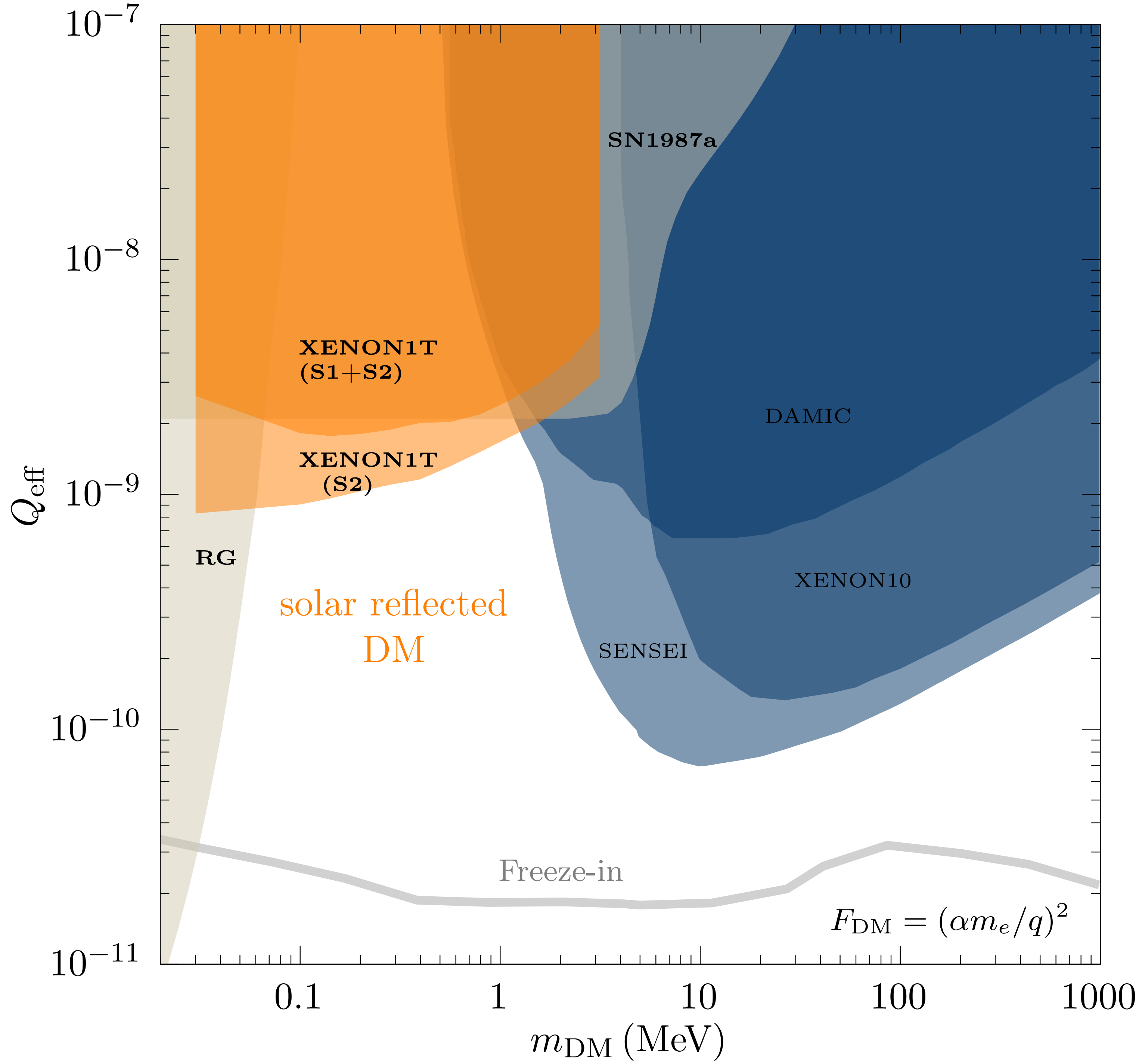


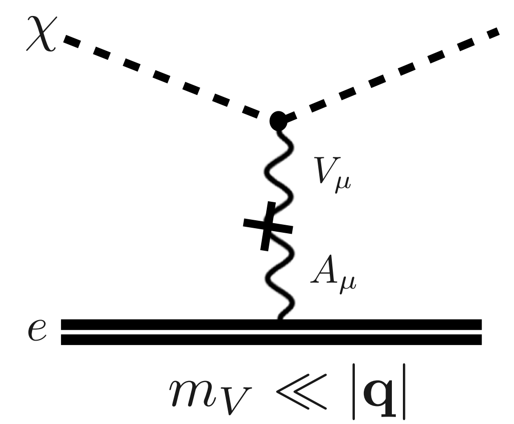
$$Q_{\text{eff}} = e_D \kappa / e$$

An, Nie, Pospelov, JP, Ritz PRD 2021

Solar Reflection of DM

Millicharged DM





$$Q_{\rm eff} = e_D \kappa / e$$

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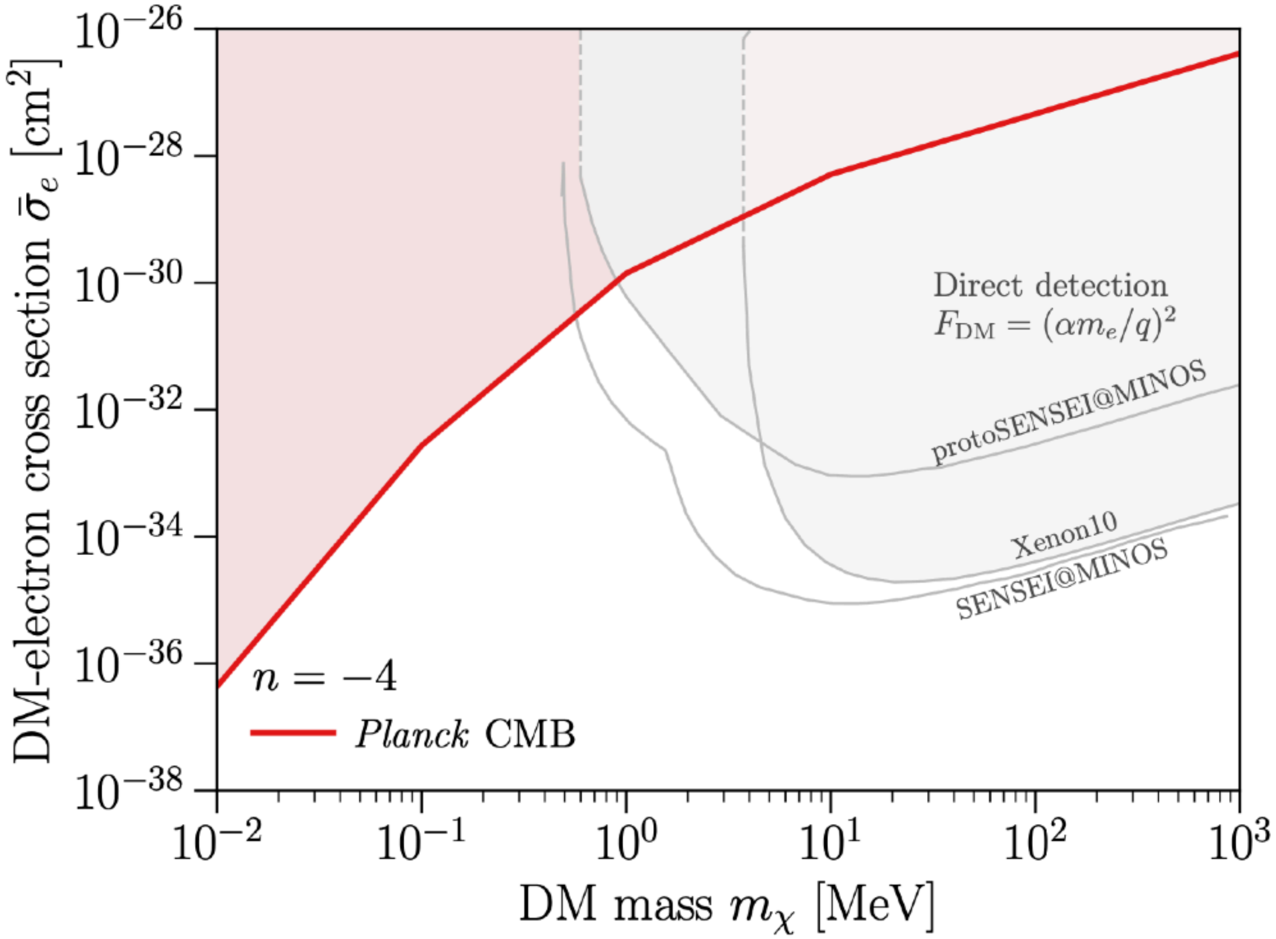
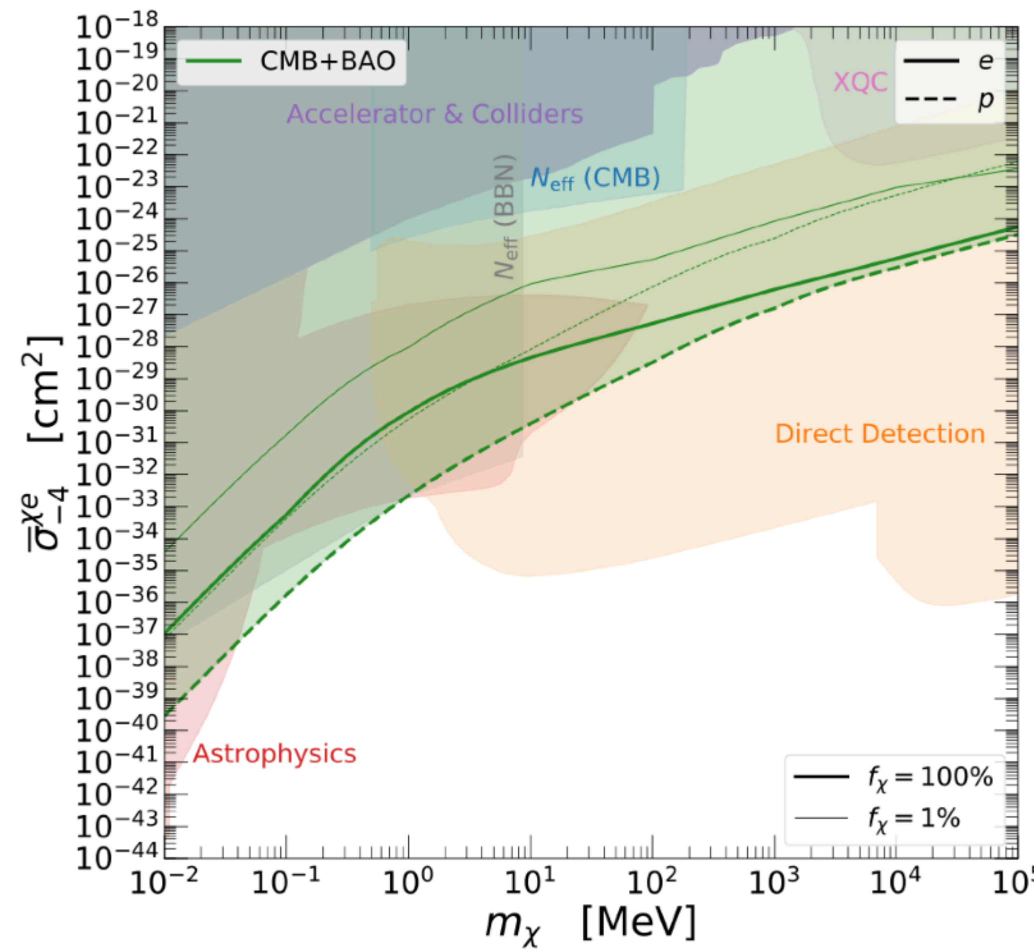
Cosmological limits

Similar sensitivity from cosmology





Nguyen et al arXiv:2107.12380

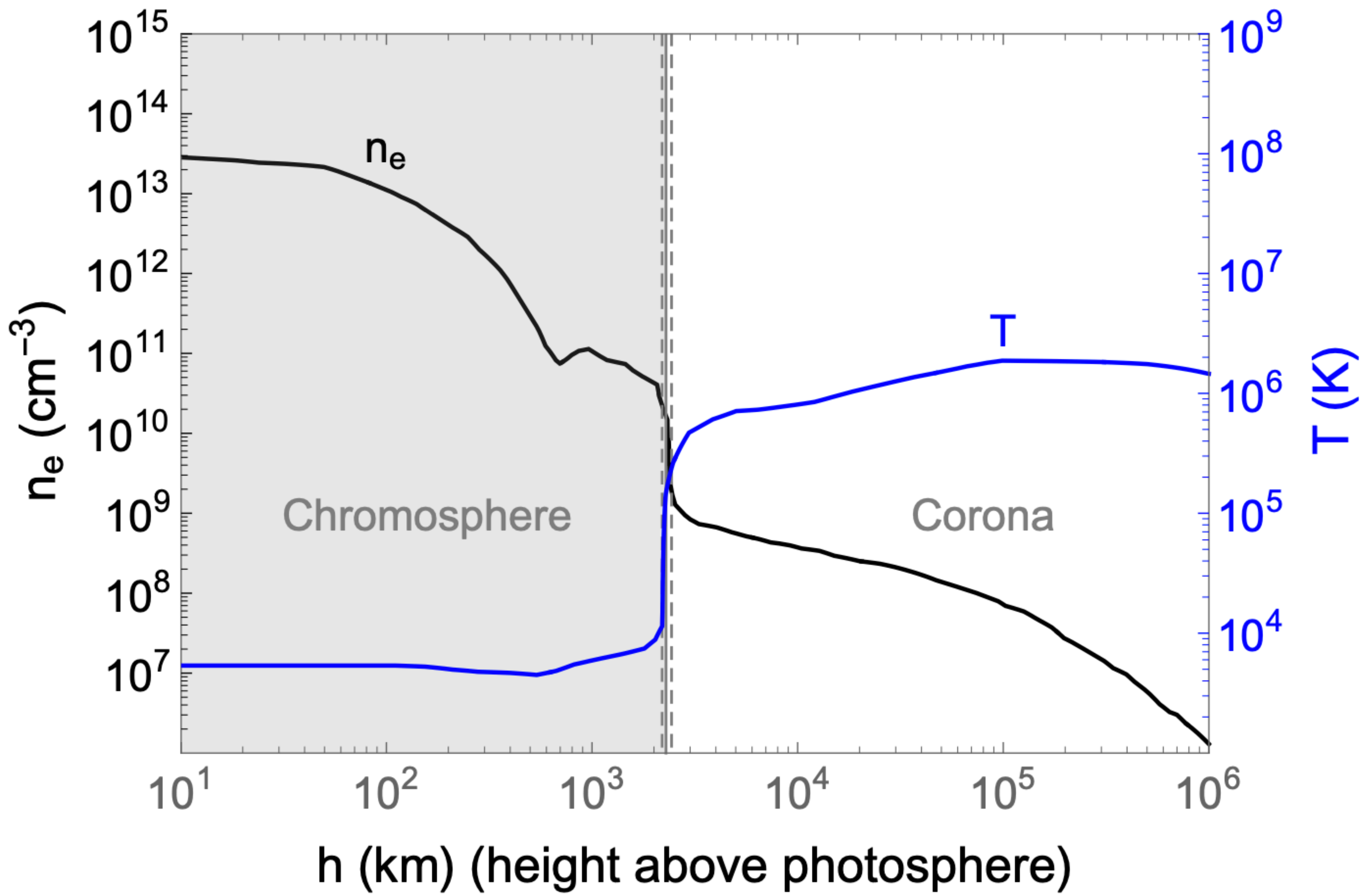
Buen-Abad et al arXiv:2107.12377v1

Reflection of DM from the Corona

Sensitivity to large couplings? (where particles don't enter the sun)

Solar corona dilute, but hot!

Very small but energetic enough flux possible



Reflection of DM from the Corona

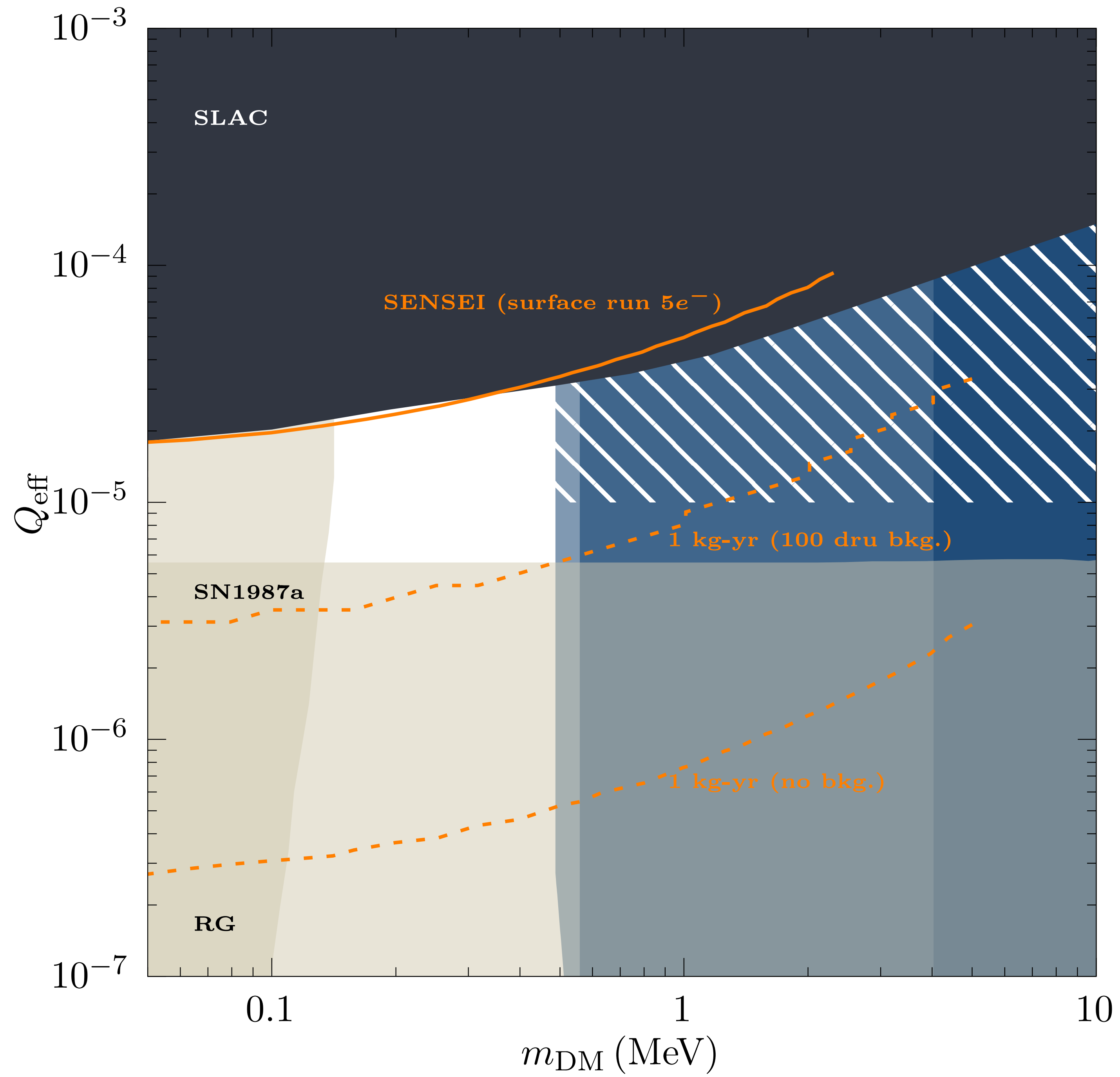
Sensitivity to large couplings? (where particles don't enter the sun)

Solar corona dilute,
but hot!

Very small but energetic enough flux possible

particles will not reach deep underground => take surface runs

(we are neglecting complications here; rough estimate)



Summary

- the number of possibilities for particle DM appears daunting (no insight on mass); however there are very well motivated cases that can serve as “prototype models” coupled through portal interactions
- direct detection aims at registering DM-atom interaction; lowering threshold, one gains exponentially
- we may harvest irreducible signal components (Bremsstrahlung, Migdal electrons, solar reflected DM) to extend the physics reach of those experiments without extra cost
- solar reflection of MeV-mass DM with couplings to electrons

  => O(10^{-4}) component to the DM flux at earth from solid angle

  => extends the reach in the “electron-scattering” channel to MeV DM mass range with optimum sensitivity at electron mass direct detection

  => cosmological bounds on DM-electron scattering for light mediator are similar but complementary; for sub-% fractional abundance, cosmological limits may disappear

Summary